Title

A Temporal and Spatial Evolution of the California Renewable Hydrogen Production Network Based on a Least-Cost Planning Framework

Author

Dailey, Emily Elizabeth

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A Temporal and Spatial Evolution of the California Renewable Hydrogen Production Network Based on a Least-Cost Planning Framework

THESIS

Submitted in partial satisfaction for the requirements

for the degree of

MASTER OF SCIENCE

in Civil and Environmental Engineering

by

Emily Elizabeth Dailey

Thesis Committee:

Professor G. Scott Samuelsen, Chair

Professor Brett Sanders

Professor Michael Hyland

Dedication

To all the teachers that believed in me and who continue to believe in me, and to my mother—
my first teacher.

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Acknowledgements

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Abstract of the Thesis

A Temporal and Spatial Evolution of the California Renewable Hydrogen Production Network Based on Least-Cost Planning Framework

Master of Science in Civil and Environmental Engineering
University of California, Irvine, 2020
Professor G. Scott Samuelsen, Chair

This thesis describes a geospatial modeling approach to identify the optimal locations for hydrogen fuel production, based on least-cost generation and transport, and provides context surrounding the selection of location buildout as well as the cost feasibility of renewable hydrogen production in California. This is accomplished by estimating and projecting California renewable hydrogen demand scenarios through the year 2050, identifying various feedstock types and locations, excluding areas not suitable for development, and selecting optimal site locations using commercial geospatial modeling software. The findings indicate that hundreds of new renewable hydrogen production facilities will be required to be deployed and commissioned in the decades preceding the year 2050. In selecting sites for development, feedstock availability by technology type is the driving factor. It is found that, around the year 2030, cost of each delivery method of renewable hydrogen will approach a price competitive position to that of gasoline. Similarly, it is found that, by the year 2050, the capital cost of each renewable hydrogen production technology will decrease such that the market will become self-sustaining.

1. Introduction

Hydrogen can be used as both a fuel source and energy carrier when produced through low and zero-carbon production pathways, stored, and later utilized in zero-emission energy conversion devices such as fuel cells. In its implementation, hydrogen addresses climate change and local air quality by shifting the paradigm within the transportation sector and as an energy storage resource [1]. Successful introduction and commercialization of hydrogen fuel use in California will be determined, in part, by the buildout of the infrastructure necessary for enabling an early market. Already, hydrogen dispensing infrastructure deployment is being guided by the Spatially and Temporally Resolved Energy and Environmental Tool ("STREET"), a method developed by the University of California, Irvine (UCI) Advanced Power and Energy Program (APEP)[2]–[4]. For hydrogen to be suitable for use as a fuel in large quantities across California and become competitive in the transportation and energy market while meeting state-mandated emission objectives, robust supply chains must be established in addition to dispensing infrastructure, and the cost of hydrogen generation significantly lowered.

The geospatial siting of renewable hydrogen production locations within this thesis will complement and mirror the work conducted by the development of STREET. STREET adopted an analytical approach to guide the deployment of hydrogen refueling infrastructure, as well as plan and optimize the size and location of the station network required to support early adoption of fuel cell electric vehicles (FCEVs). STREET employed geospatial analysis techniques to determine the spatial and temporal hydrogen refueling infrastructure rollout necessary to ensure the demand for each network (community of stations) was met while remaining easily accessible to the user. The development of STREET included a comprehensive assessment of population centers that would maintain adequate purchasing power to adopt FCEVs. Census data were assessed and used to establish potential FCEV market areas, and GIS techniques were then used to provide high resolution buildout recommendations for these market areas. The objective of STREET was to establish and “initiate FCEV commercialization in numerous California markets” by providing the planning and coordination analysis needed to ensure that investments in this space are effectively and efficiently used [4].

To further the work accomplished by STREET, a complementary analysis is necessary to plan and coordinate the rollout of renewable hydrogen production facilities that will provide fuel to the network of hydrogen refueling stations created by STREET. Similarly, these production facilities will further the use of hydrogen as a means to achieving net-zero energy systems in the future.

To this end, a key factor is scale (building facilities in high numbers) and learning through deployment. This will help to instill a level of consumer confidence in the early adopters of the technologies. The relatively high current costs and lack of visibility of the cost and timeframe for required subsidies and incentives to achieve a self-sustaining renewable hydrogen sector is a barrier to state action to support the scale-up of renewable hydrogen production. In order to provide a basis for policy development and planning, an analytically sound analysis is needed to (1) forecast the spatial and temporal demand for renewable hydrogen generation coupled with the development of cost-optimized build-out scenarios for the renewable hydrogen production network needed to serve the demand, and (2) shed light on the total investment needed over various time horizons, the level of government subsidies and incentives, and the potential time and conditions under which the sector can become self-sustaining without incentives. As with the resource potential studies that have been conducted for wind and solar to identify areas of high potential for project development, such an analysis does not require defining precise locations and sizing of facilities to be built [5], [6]. Rather, the analysis needs to provide insight on areas likely to see substantial development activity and define actions needed to support realization of the required renewable hydrogen production network.

The analysis does require, however, a thorough analysis of demand, input materials, and feasible locations for implementation of the hydrogen production technologies. Electrolysis using renewable electricity as feedstock is one of the most promising pathways for renewable hydrogen production, offering the advantage of modularity to permit deployment across a broad range of project sizes. Similarly, anaerobic digestion offers a pathway to producing biogas, which can be reformed into hydrogen. It offers the advantage of the ability to utilize biomass feedstock of high moisture content, like livestock manure or organic municipal solid waste, much of which is abundant throughout the state of California. Finally, thermochemical processing of biomass with lower moisture content can be utilized as a pathway to hydrogen production in a manner similar to anaerobic digestion. This pathway’s key advantage is its ability to process forest thinning waste, agricultural residue, and other waste plant life.

To meet the need for such an analysis, this thesis develops and applies an analytical approach to the geospatial siting of key renewable hydrogen production technologies within the context of developing a self-sustaining network throughout the state by the year 2050, effectively mirroring the role of STREET in guiding the development of the hydrogen fueling network.

1.1 Goals

The goals of this research are to:

- Develop, validate, and implement an analytical approach to define optimized temporal and spatial build-out deployment scenarios and appropriate siting of electrolytic, thermochemical, and anaerobically digested renewable hydrogen production facilities across the state of California, and
- Assess the feasibility of the temporal and spatial buildout of each of these technologies

1.2 Objectives

To achieve these goals, the objectives of this thesis are:

1. Characterize the state of the art of electrolyzer, thermochemical, and anaerobic digestion technologies, including cost, performance, and siting requirements.
2. Develop and assess temporal and locational demand scenarios for renewable hydrogen.
3. Characterize the current and future cost of the technologies (primarily capital cost and efficiency) as primary input to hydrogen delivery chain cost.

4. Integrate hydrogen delivery chain cost assumptions from HDSAM into the framework.
5. Create a model spatial and temporal buildout plan of renewable hydrogen production via the various production technologies

2. Background

From the genesis of life, all energy has come from the sun, using varying amounts of heat, pressure, and time to create the fuels consumed by modern technologies. For example, solar power is generated using solar irradiation and is essentially instantly generated, whereas coal, oil, and natural gas have consumed energy from the sun over millions of years to heat and pressurize biomass into a condensed, dispatchable fuel. The rate at which we consume these resources must equal the rate at which they are naturally replenished on Earth in order to maintain a sustainable society [7]. The current demand for energy services necessitates the use of more renewable and sustainable energy sources and conversion technologies. Current practices are simply not sustainable.

In addition, to stabilize global mean temperatures and avoid further environmental destruction, net emissions of carbon dioxide must approach zero [8]. With this motivation, nationally and globally, the state of California has become widely regarded as a prominent leader in the pursuit of environmental stewardship. The state openly accepts the findings of scientists and academics that confirm the persistence of global warming and climate change, and as a result, historically significant attention has been directed to emissions reduction and decarbonization. In recent decades, California has struggled with air quality challenges, a reduction of supply and quality of water from the Sierra snowpack, a rise in sea levels, damage to marine ecosystems, and an increase in human health-related problems, including infectious diseases and asthma. Similarly, some of the state's most prominent industries—agriculture, wine, tourism, skiing, fishing, and forestry—have felt the impacts of global warming on annual yields [9]. Reducing anthropogenic emissions and decarbonizing energy services to combat the effects of climate change benefits California in both the short- and long-term.

Ambitious goals for the reduction of greenhouse gases (GHG) and air pollutants have been set by the state in an effort to reduce the state's negative global climate impacts. Assembly Bill (AB) 32, the California Global Warming Solutions Act of 2006, a long-term, comprehensive piece of legislation, was passed by the state to mandate that GHG emissions must be reduced to 1990 levels by 2020. In order to coordinate between the state and the community, industry, and academia, AB 32 established the Air Resources Board (ARB). The ARB adopts rules and regulations in an open public process to achieve the most technologically feasible and cost-effective GHG reduction strategies. It is the belief of the state that "investing in the development of innovative and pioneering technologies will assist California in achieving the 2020 statewide limit on emissions of GHG" [10]. In this process, it is in the interest of the state to explore the options that would help achieve these goals.

Decarbonization and emissions reduction can be achieved through various means, including electrification and power generation from renewable resources such as wind and solar [1][8]. To address intermittency of these resources, batteries would also be placed as energy storage mechanisms throughout the grid. However, the use of batteries does not provide the potential for enough storage to meet the world's electricity demand. To provide the world with enough battery capacity to accommodate a complete shift to renewable solar and wind power, 19, 981 TWh of storage would be needed. This would require 3,144 Mt of lithium and 25, 815 Mt of cobalt; Yet, only approximately 53 Mt of lithium and 25 Mt of cobalt in reserves are available worldwide. There are simply not enough raw resources to facilitate this shift, and this is merely one concern. A shift to pure electrification of energy services would also be costly and would result in a great level of self-discharge and performance degradation of the equipment over time [7].

Batteries also lack the performance characteristics to become the central source of energy storage. Round-trip efficiencies studied primarily through laboratory testing found an average of 60% round-trip efficiency for various lithium-ion batteries, many of which were subject to performance-based incentives. Primary reasons for inefficiencies include self-discharge, cooling, transforming, and balancing of plants. In the future, it is unlikely that a more energy-dense battery chemistry will be found, as the reduction potentials of the lithium and cobalt half reactions are very favorable. It is plausible to build a battery with more abundant raw materials in the future, but it remains unlikely that this battery's energy density would be lower than that of a lithium-ion battery. This "future" battery would also still be subject to self-discharge [7]. This only describes the pitfalls of batteries as they pertain to worldwide energy storage. A number of specific energy services are difficult to electrify, further demonstrating that batteries alone will not suffice as a means of energy storage. For example, use of battery electric vehicles, although feasible and beneficial to society already, is subject to its own set of obstacles [8]. Batteries are generally not capable of rapid fueling, long range uses, or large payloads, making electrification for these needs difficult.

The sources of renewable power used in electrification would also remain subject to significant variability dependent on the time of day, the season, and the weather, which render them unreliable during certain times of day. This is a concern, given widespread economic dependency on electricity necessitating greater than 99.9% reliability of power delivery [8]. With greater implementation of renewable resources on the grid, over generation from renewables is already posing a delivery issue for electricity service providers. As shown in Figure 1, renewable power greatly lessens the net load of power supply needed from the service provider during the middle of the day, when renewables are generating the most power. With less demand needed on the grid, due to greater use of wind and solar power during the day, a high ramp rate is required to compensate for times when those renewables are not available. Greater presence of renewables brings a change from previously using primarily dispatchable fossil fuels as sources for power [11].

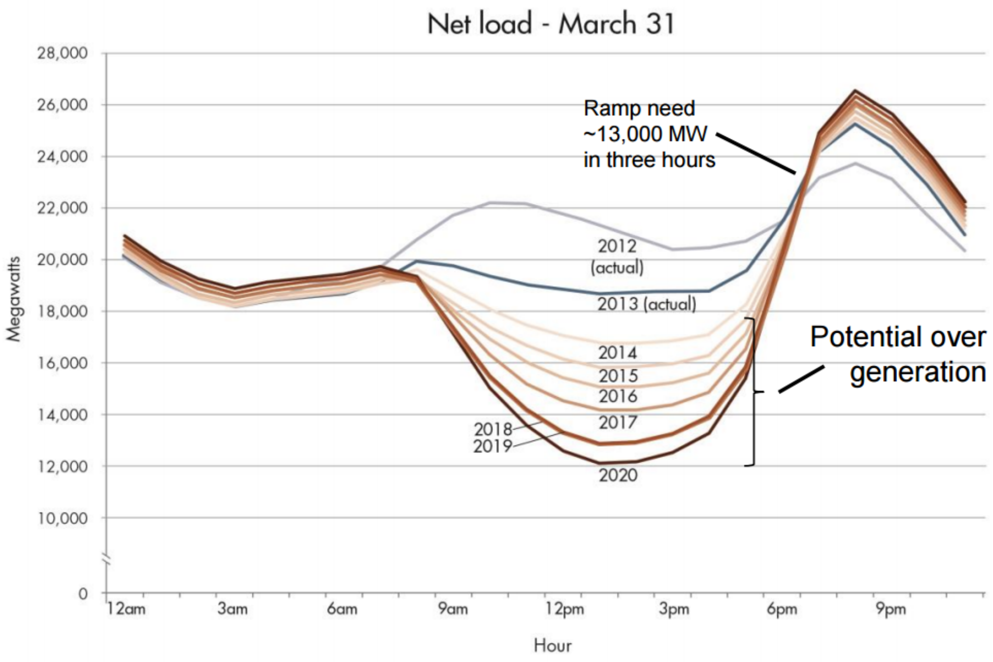

Figure 1: CAISO Duck Curve [11]

Many sources are available to shift society to a more sustainable energy future, but often cost is a driver toward or away from adoption. In recent years, the price of solar and wind power has drastically fallen, allowing for further adoption of these technologies.

Vast implementation of renewable power alone is not enough; to fulfill energy service demands, a system of energy storage and clean, dispatchable power generation to rival that of conventional fossil fuels is needed [7]. To this end, the use of hydrogen fuel poses a solution. Hydrogen can be used as a fuel source due to its flexibility as an energy carrier and its role when produced through low and zero-carbon production pathways, stored, and later utilized in zero-emission energy conversion devices such as fuel cells. For difficult-to-electrify services such as long distance transportation, hydrogen fuel and storage are some of the most promising means for delivery [8]. Shown in Figure 2 are production pathways for renewable hydrogen from a variety of feedstocks. A variety of means are available to produce hydrogen from various feedstock types through different technologies.

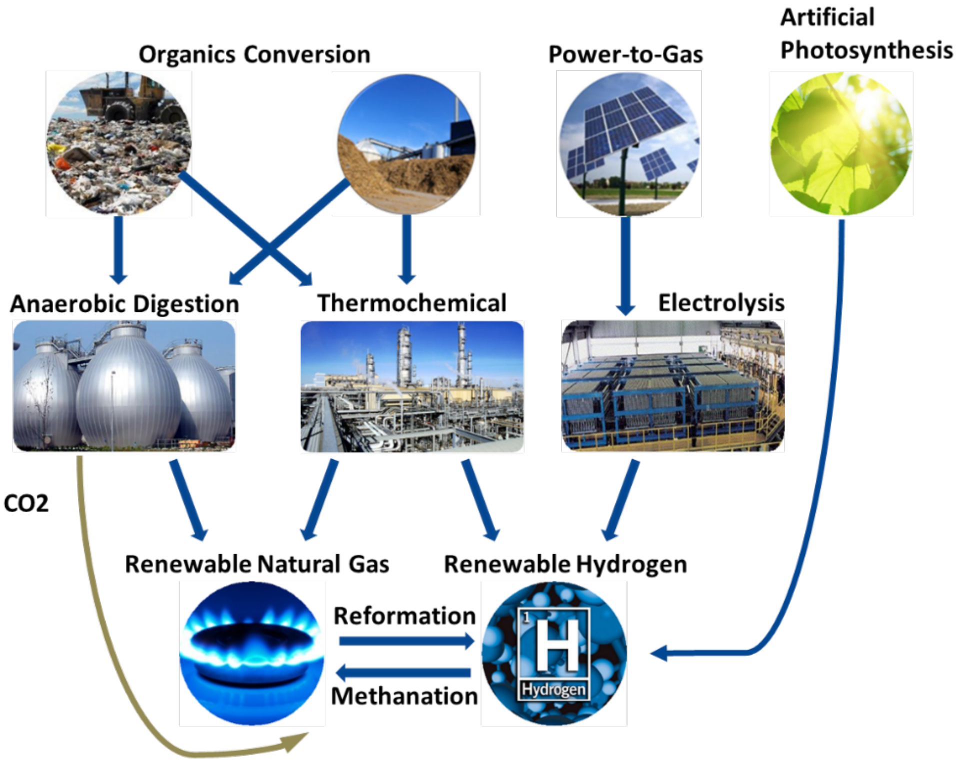

Figure 2: Production Pathways for Renewable Hydrogen [12]

Hydrogen produced by biomass provides a means of producing hydrogen by using waste from a variety of sources. Based on the moisture content of the discarded biomass, either thermochemical conversion or anaerobic digestion can be used to produce syngas. Thermochemical conversion, specifically gasification, can also produce a hydrogen stream directly without the need of a reformer. Gasification is a commercially mature technology, which is based upon partial oxidation of biomass with a low moisture content to create a gaseous mixture of methane, carbon monoxide, carbon dioxide, nitrogen, and hydrogen.

Adding oxygen and steam produces the syngas, with a hydrogen to carbon monoxide ratio of 2:1, which undergoes a water-gas-shift reaction to produce hydrogen. Technical concerns with gasification include low thermal efficiencies and production of NO_x, which can lead to health and operation costs [13].

Anaerobic digestion is similar to gasification, in that various biomass feedstock sources can be used in conversion to syngas. Anaerobic digestion is a naturally-occurring biological process, wherein naturally occurring bacteria generate methane by breaking down organic substances. This process can occur in environments with or without oxygen, and it produces a syngas with around 60% methane and 40% carbon dioxide content. However, the syngas contains trace amounts of water, sulfur compounds, halogenated organic compounds, metals, and oxygen. These impurities must be removed, along with the carbon dioxide, to produce usable biomethane [14].

To accompany an anaerobic digester, a reformer is required to produce hydrogen from the produced biomethane. Steam methane reforming (SMR) is commonly used for this process, wherein the biomethane is heated to extract hydrogen. This process currently is responsible for producing 80-85% of all current hydrogen [15]. This reforming can achieve a thermal efficiency of up to 85% based on the high heating value, which makes it a favorable economic choice for hydrogen production; however, most hydrogen produced via SMR is done using natural gas. SMR provides environmental benefits when coupled with biomethane produced from discarded biomass, rendering it a carbon-neutral process as it produces some CO_2 emissions throughout its process [13].

Hydrogen fuel can be produced via the renewable curtailment in California, in order to combat the inability to utilize curtailed power. It is estimated that from 2017 renewable power curtailment in California, 7.4 - 11.1 million kg of hydrogen could be produced to power 34,500 - 51,700 hydrogen fuel cell electric vehicles for a range of 15,000 miles per year [16]. To utilize curtailed renewable power for the production of hydrogen, a process called power-to-gas (P2G) is used. This process converts the electrical power into hydrogen via electrolysis, or the splitting of water. Three popular types of electrolyzers are available of which the most promising is the solid oxide electrolyzer [7] .

The most commonly used electrolyzer is the alkaline electrolyzer, which use a liquid electrolyte that must be replenished from time to time. These electrolyzers typically achieve efficiencies of 50-60% based on the lower heating value of hydrogen, and they are the most developed of the technologies [13]. The proton exchange membrane electrolyzer uses a membrane of Nafion, and typically achieves efficiencies of 55-70% [13]. Both of these electrolyzer types operating at a relatively low temperature when compared to the solid oxide electrolyzer, and because of this, they require the use of expensive precious metal catalysts. Solid oxide electrolyzers (SOE) have high system efficiencies primarily due to their high operating temperature, ranging from 800-1300 K. This “eliminates the need for expensive catalysts and increases conversion efficiency and system integration opportunities” [7]. Because of this, they can reach efficiencies of 85-90% [13]. These electrolyzers require less electric input due to their high operation temperature, and they can be operated dynamically alongside the fluctuating presence of renewables on the grid. Despite the risk of material degradation that accompanies these high operating temperatures, SOEs have great potential to assist in the implementation of widespread hydrogen fuel use [7].

Lastly, artificial photosynthesis can be used for direct production of renewable hydrogen from water, carbon dioxide, and light. This process is largely pre-commercial and is primarily conducted in research laboratories. It is unlikely to become prominent prior to the year 2030 [12]. For this reason, analysis and projection of potential for this technology remains uncertain. However, as the need for zero-carbon fuels continues to increase, it is plausible to see this technology emerge as a prominent means for hydrogen production.

In order for hydrogen to be suitable for use as a fuel in large quantities across California and become competitive in the transportation and energy market while meeting state-mandated emission objectives, robust production facilities featuring various technologies must be established. Because hydrogen can be produced through a variety of feedstocks and by a variety of technologies, options for selection and placement of these production facilities exist. The greatest issue prohibiting commonplace use of hydrogen fuel is the lack of storage, transmission, and distribution of the fuel. These issues precede the establishment of an economically and technically sound hydrogen economy. Both distributed production coupled with trucking and the injection of hydrogen into existing natural gas pipeline infrastructure are considered as a promising means of distribution [7]. These challenges further the need for meaningful selection of hydrogen production technology siting.

Little work on the spatial and temporal deployment of these technologies has been completed to date. In this thesis, ArcGIS is used to select candidate locations for electrolyzer, anaerobic digester, and thermochemical conversion installation based on a variety of parameters to meet locational demand scenarios over time to serve transportation and other uses. This work serves to address this gap in understanding; a reasonable spatial and temporal development strategy that considers technoeconomic analysis, feedstock availability, and policy framework shows that the adoption of these technologies is both sensible and within reach. Through the illustration of buildout progressions for each technology for a variety of scenarios, state agencies, policy-makers, and the private sector can visualize the implementation of these facilities.

3. Approach

3.1 Task 1: Characterize the state of the art of electrolyzer, thermochemical, and anaerobic digestion technologies, to determine siting requirements

This task defines the footprint, terrain, zoning restrictions, and access to utilities that are required by the technology. This develops a fact base to assess technology characteristics, using data sources as found in the literature review. In this task, existing data relating to feedstock availability is spatially resolved to determine location potential for technology development.

3.2 Task 2: Develop temporal and locational demand scenarios for renewable hydrogen

In this task, STREET and ARB station network build-out data are used as demand input. Similarly, the amount of necessary temporal buildout for each technology is determined, based on feedstock availability, location, and renewable hydrogen demand. GIS layers relevant to the siting requirements are compiled, including: population density, zoning, land use, environmentally protected areas, electric transmission infrastructure, rail and highway maps, and land management classifications. The scenarios are then framed and solved within ArcGIS, using the location-allocation tool and spatial analyst suite of tools.

3.3 Task 3: Characterize the current and future cost of the technologies (primarily capital cost and efficiency) as primary input to hydrogen delivery chain cost

The candidate development sites, as provided by the ArcGIS analysis, are assessed for capital cost based on facility size and learning curve analysis. Efficiency of each technology is discussed to provide an overview of development feasibility. In this task, cost for supply of organic feedstock and renewable electricity are discussed in the context of the renewable hydrogen production methods to provide a framework for overall cost of production.

3.4 Task 4: Integrate hydrogen delivery chain cost assumptions from HDSAM into the framework

The costs associated with the candidate locations are integrated with the delivery chain cost assumptions used in the HDSAM model, provided by Argonne National Lab. This provides a cost projection for plant-gate-to-dispenser cost per kilogram of renewable hydrogen produced by each mode. This cost projection is applied to the cost of feedstock and technology capital cost to provide a holistic assessment of technology feasibility.

3.5 Task 5: Create a spatial and temporal buildout plan of renewable hydrogen production via the various production technologies

In this task, the recommended buildout plan is presented, in 5-year increments, for each scenario. Similarly, the cost associated with each scenario is presented and buildout progression is shown. The results, recommendations, and relevancy of each are discussed. Areas for future work are presented and discussed.

4. Task 1 Results: Technology Characterization

To assess feedstock availability and siting, ArcGIS, a commercial geospatial modeling software, was used. ArcGIS allows for the analysis of spatial data and has various capabilities that can be used to create a network of hydrogen production technology sites [17]. To achieve this, a variety of feasibility prescreening analyses of feedstock were conducted. This portion of the analysis focuses on assessing exclusion criteria, feedstock availability, and primary infrastructure required for each technology across the state. These exclusion criteria are summarized in Table 1.

Facility Type	Feasibility Screening Criteria
Electrolyzers	High wind and solar resource areas with transmission access or transmission access within 50 miles of demand
Dairy Anaerobic Digesters	Existing dairy farms in clusters of 5 to 10 with an anchor farm of >5,000 milking cows
Food and High-moisture Organic Anaerobic Digesters	Along current and historical landfill disposal routes with adequate area for 100,000 MMBtu per year facility size Existing wastewater treatment and resource recovery facilities
Thermochemical Conversion Facilities	Forest areas and agricultural areas (crop residue) with site suitable for 50,000 kg/d RH2 facility size outside non-attainment areas
SMR Facilities	Outside non-attainment areas close to natural gas transmission and highway transport
Liquefaction Facilities	Co-located with SMR facilities or production facilities with production capacity of minimum 30 tonnes hydrogen per day

Table 1: Screening Criteria for Renewable Hydrogen Production Technologies [12]

Feedstock availability was the driver in the site selection for each method. Minimizing distance to feedstock was assumed to be a key method of minimizing overall cost, as transportation over existing infrastructure modes is costly. Shown in Figure 3 are primary resource areas for various feedstock types. For the analysis, it was assumed that solar and wind resource would supply electrolyzers, high moisture organic waste (food waste) and dairy manure would supply anaerobic digesters, and agricultural crop residue and forest trimmings would supply gasification facilities. For electrolysis, it was assumed that water was available on-site, assuming that electric transmission and renewable power resources exist within reasonable proximity to the state’s primary water supply (shown in Figure 4). It is reasonable to assume this, given the water required for electrolysis is minimal and the state’s water resources are far-reaching [12]. SMR and liquefaction facilities are ancillary equipment to the primary production technologies and were sited within the analysis as well. For all technologies, feedstock identified in locations with elevation greater than 1000 ft. were excluded, as it was assumed that access to this feedstock would be limited and cumbersome due to the grade of the roads leading to these areas.

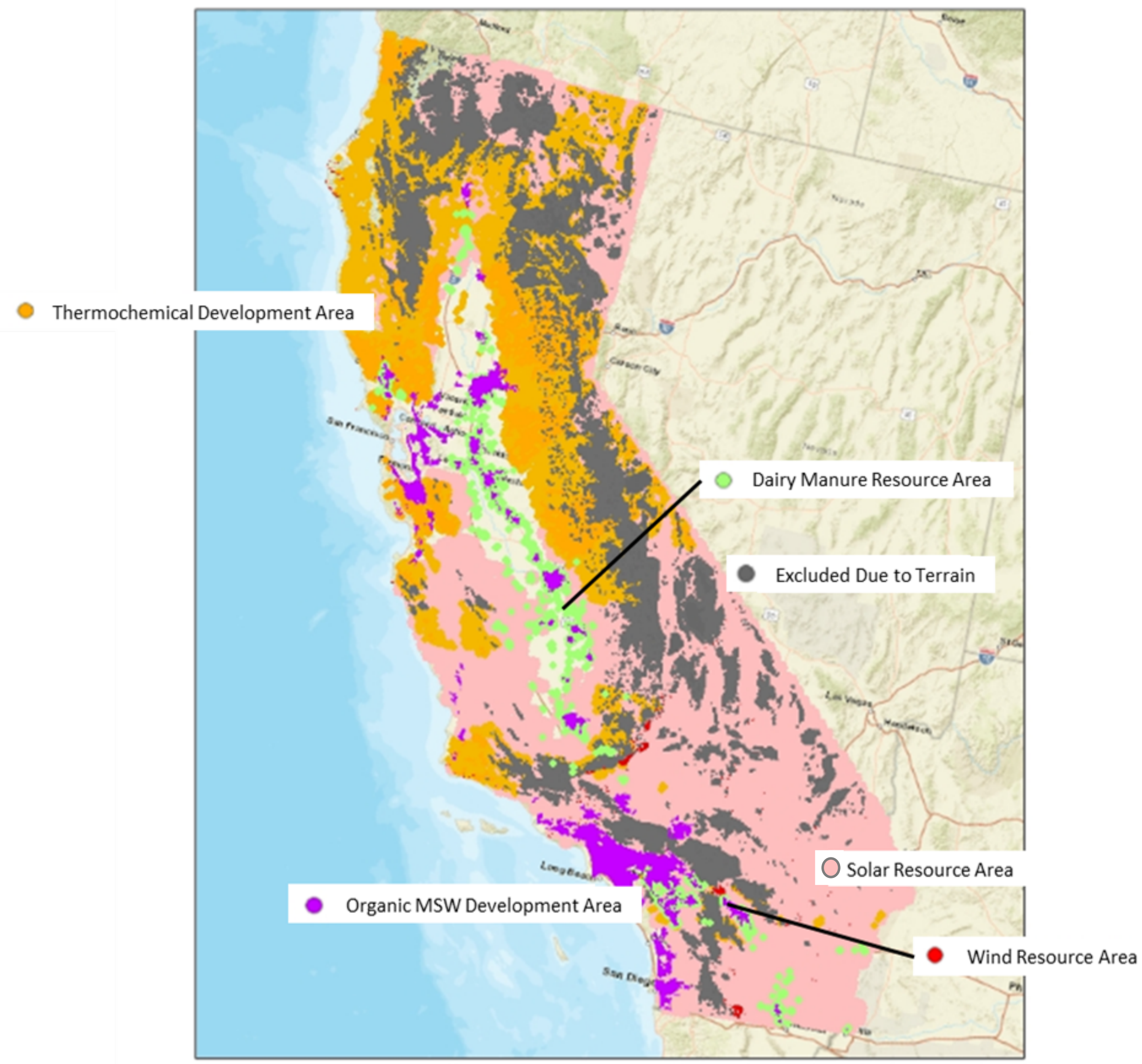

Figure 3: Renewable Hydrogen Resource Availability [18][19][20][21][22][23]

Figure 4: Primary water resources statewide [12]

In this analysis, both thermochemical and SMR technologies were excluded from some areas in an attempt to reduce environmental impacts to these communities, as many of the communities deemed spatially suitable for these technologies are subject to other negative environmental impacts or risk factors. Therefore, the colocation of these facilities in communities deemed at-risk for environmental injustices is unjust. SMR, in comparison to other methods of hydrogen production, poses the highest risk of abiotic depletion, acidification and eutrophication potential, global warming and ozone depletion potential, and human toxicity, due to the process of heating input methane that produces CO_2 as a by-product [24]. Thermochemical production is excluded for similar community impact reasons. Although emissions from the thermochemical process are lesser when the syngas produced is not combusted, attention must still be given to the emissions of these facilities [25].

To assess and determine areas not suitable to host these technologies, CalEnviroScreen was used. CalEnviroScreen is a tool developed by the State of California to identify communities most affected by anthropogenic emissions and pollution sources as well as population characteristics that would lead a community to higher environmental damage. CalEnviroScreen's cumulative impacts scoring provides an environmental justice framework to assess the impacts of integrating renewable hydrogen production technologies across the state by assessing a community on both a scientific and empirical, human level. CalEnviroScreen is composed of 19 indicators that incorporate contact with pollutants, medically sensitive populations, race, age, and socioeconomic factors [26]. These indicators serve to quantify a community's population characteristics score and pollution burden score, and communities with high scores are placed in high risk categories. High risk areas were then excluded from this siting analysis.

Classifications for criteria pollutant nonattainment through CalEnviroScreen is done at the county level, and three different pollutants were considered in this analysis—ozone, $PM_{2.5}$, and NO_x. Because SMR is known to produce pollutants that can be harmful to the public in large amounts, attention must be given so as to not site the technology near known existing sources of pollution such as freeways or ports. Figure 5 shows areas (in red) excluded from the siting of these two technologies—areas classified as CalEnviroScreen disadvantaged communities, which are also in EPA-classified ozone and $PM_{2.5}$ non-attainment status.

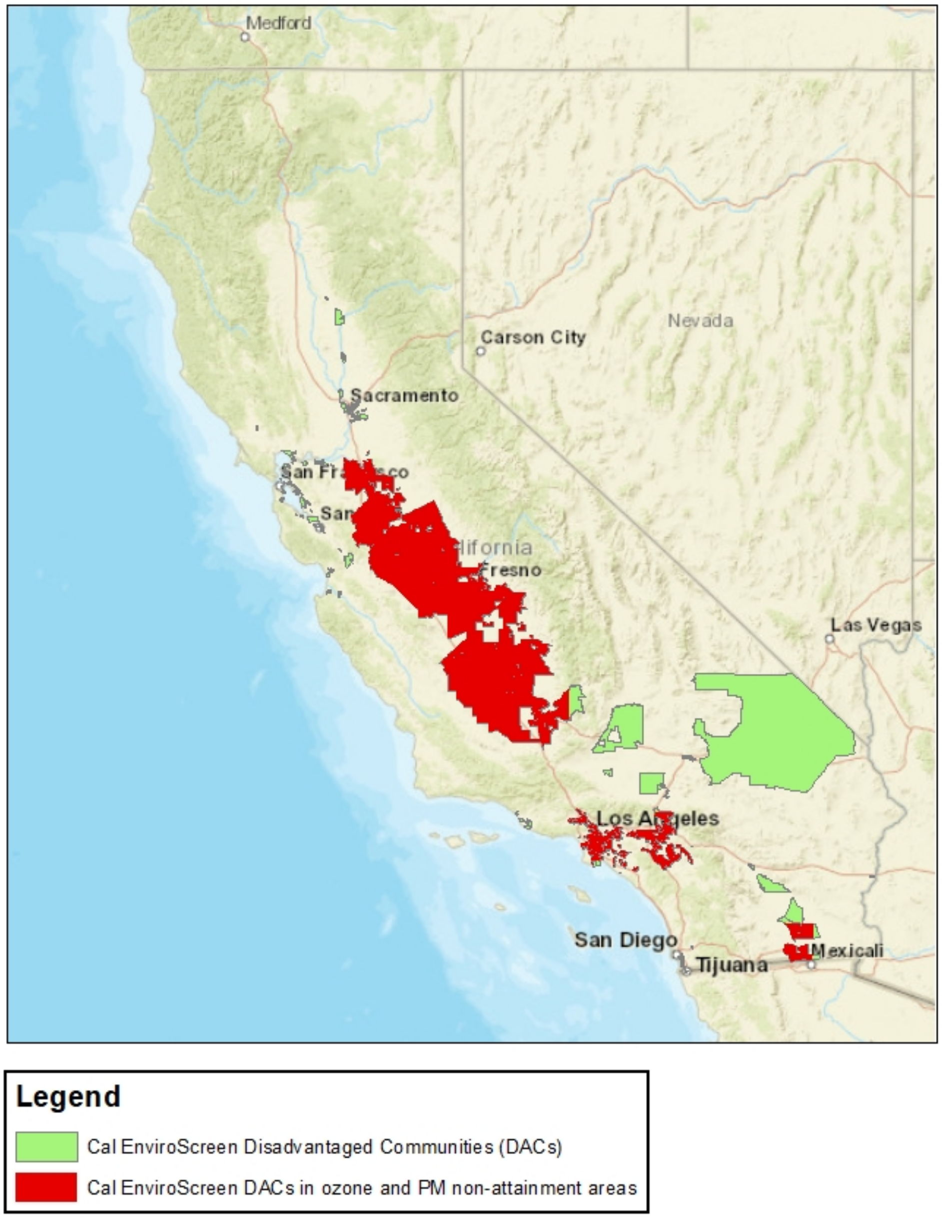

Figure 5: Excluded areas for thermochemical production and SMR [27]

The final prescreening criterion was proximity to existing transportation infrastructure. Locations were selected such that access to rail lines, truck lines, the electric transmission system, and the high-pressure natural gas transmission system was prioritized. Ensuring access to this transportation infrastructure allows for the produced hydrogen to be easily transported to the end users, as well as for the feedstock to be easily transported to the hydrogen production facility. Specific infrastructure proximity requirements for each production technology varied and are summarized in Table 1. Transportation infrastructure as used within the analysis is shown in Figure 6.

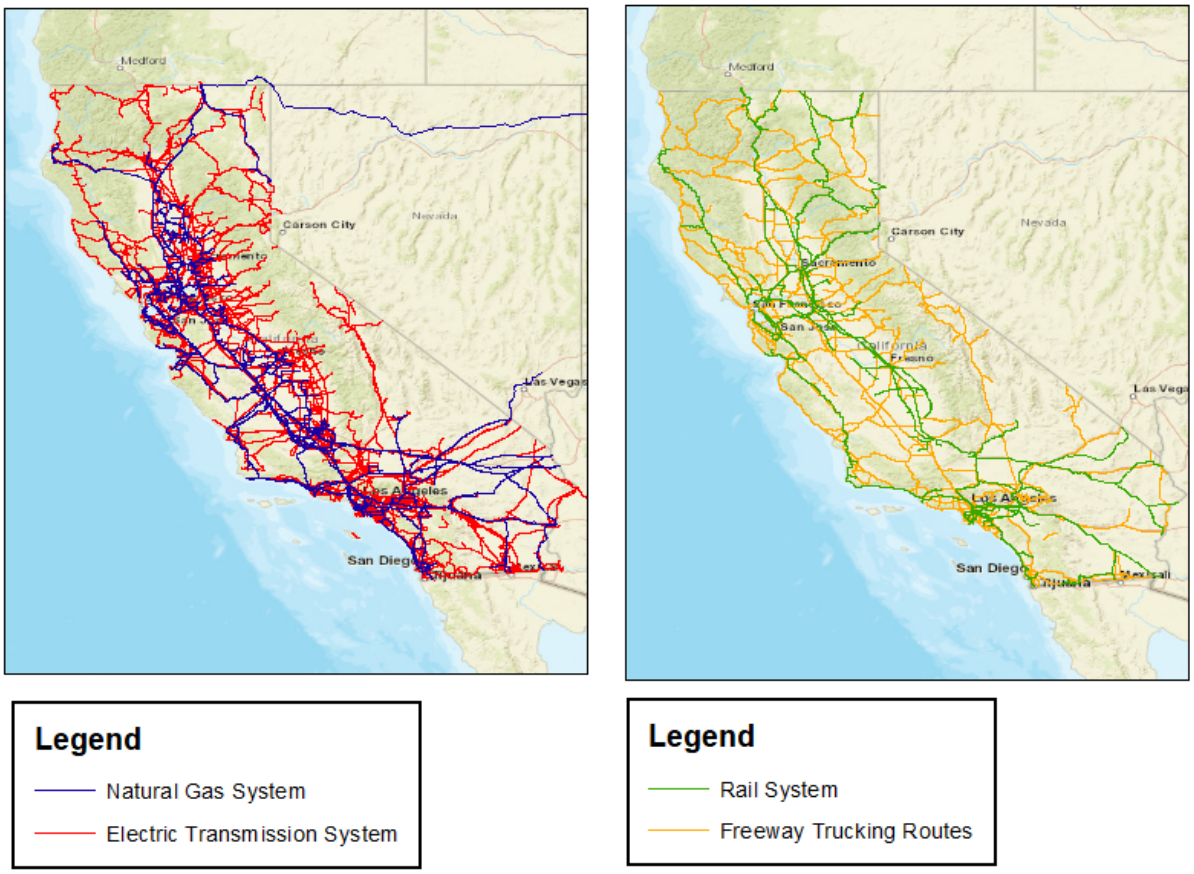

Figure 6: Electric and natural gas transmission (left)[28][29] *, rail system and freeways (right)*[30][31]

5. Task 2 Results: Demand Scenarios

After prescreening criteria were applied, candidate sites were created within areas that meet the requirements of each technology in order to develop the geospatial rollout for each of the demand scenarios. Specifically, the location-allocation tool within ArcGIS was used to choose optimal locations for each technology type such that the feedstock is supplied to the location most efficiently [17]. This tool requires two inputs: candidate locations and available feedstock locations. Each input was processed in the same format for all technologies considered. A density metric for each feedstock was created by resolving the appropriate feedstock GIS location data, with prescreening exclusions applied, to a 4km by 4km grid. Technological conversion efficiencies were then applied to the grid points to determine a Kg/H_2 per day value at each density metric point. Similarly, candidate location points were generated within a specified buffer zone surrounding the infrastructure needed for each technology (i.e., freeway access, natural gas transmission system, high voltage electric transmission) after prescreening exclusions were applied.

The location-allocation spatial analyst tool within ArcGIS was then used to select sites based on maximizing the efficiency of supplying feedstock to the technology site. Within the location-allocation tool, the maximize capacitated coverage method was applied to allow the maximum amount of available feedstock to be supplied to a candidate location without exceeding the determined capacity limit for each technology. This method allocates the demand points to the selected candidate site such that distance from demand point to candidate site is minimized while meeting the facility’s capacity. Similarly, an impedance value, or the service area for the technology, was determined for each technology. This value restricted the distance that the density points could be transported before reaching the selected candidate site. For all technology types, this value was set to 2 miles; this meant that the available feedstock at a density metric point could not travel more than 2 miles in order to reach the sited technology location. An example of the process flow used to determine candidate development sites for thermochemical conversion facilities is shown in Figure 7.

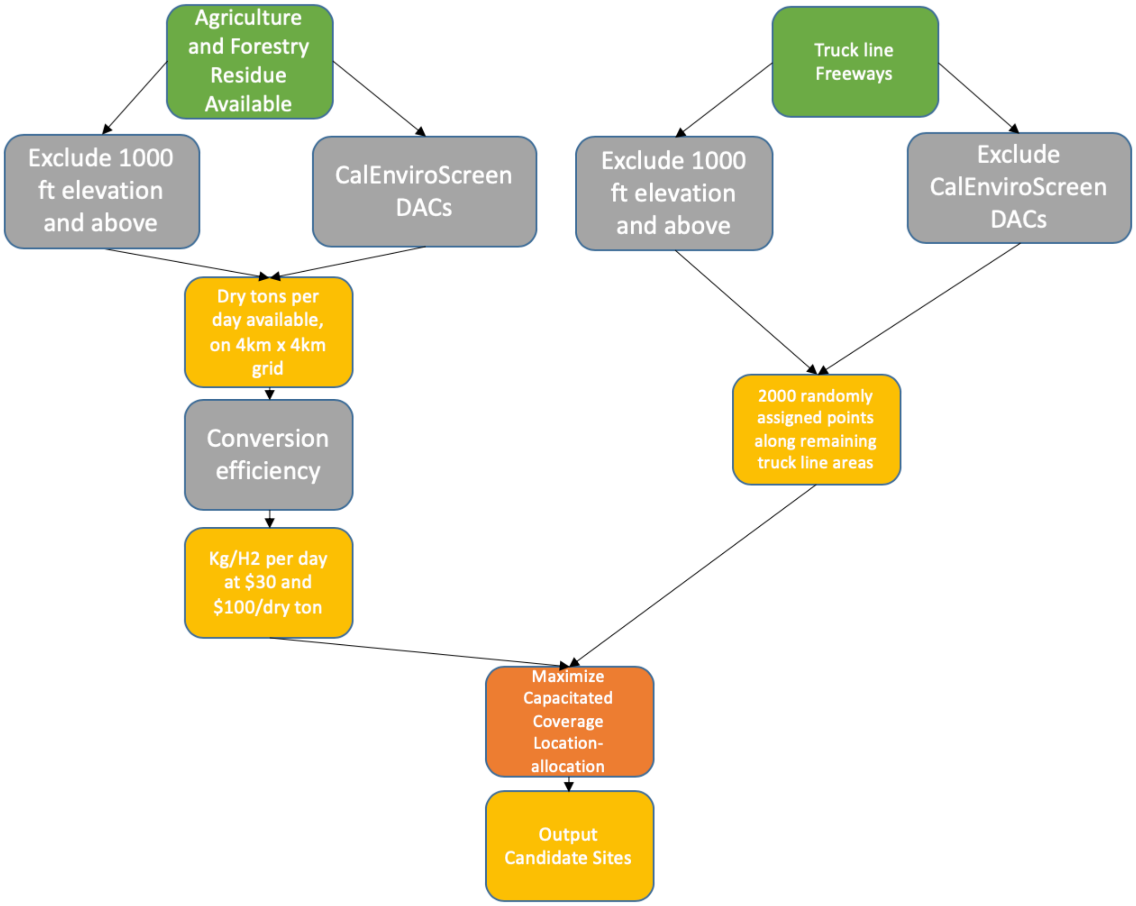

Figure 7: Process flow for ArcGIS location-allocation analysis.

Examples of candidate sites and feedstock availability sites, used in the siting of candidate electrolysis facilities are shown in Figure 8. The amount of available feedstock varied by technology type, so the amount of candidate sites was adjusted to keep the analysis process the same for each.

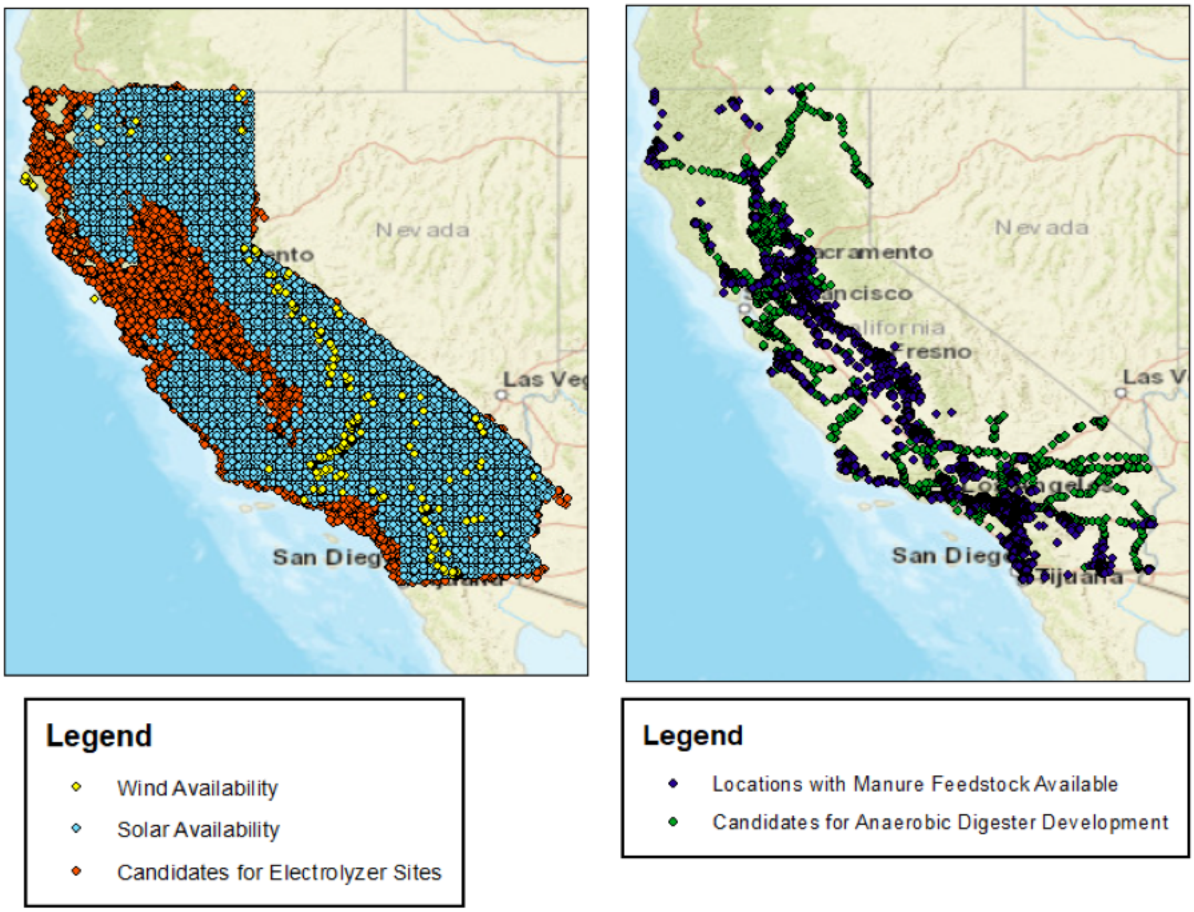

Figure 8: Feedstock density sites and candidate sites for two technologies

The demand scenarios used in the analysis were developed as part of the Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California (“Roadmap”) work in order to determine the scale of renewable hydrogen production that will be necessary in the future. Six comprehensive demand scenarios were developed in order to provide a framework for the emerging renewable hydrogen market, in light of the uncertainty in which technologies will become the most prominent. The amount of facilities per scenario was calculated based on the projected statewide hydrogen demand over time.

Sources for potential renewable hydrogen demand within California include light-, medium-, and heavy-duty vehicle use, rail and marine transportation, refining, storage, power generation, residential and commercial applications, ammonia, and export. These sources were integrated into the demand scenarios within the Roadmap effort, in order to provide a comprehensive overview of the future use of renewable hydrogen within the state [12]. The largest percentage of these sources relative to the others was light-duty vehicle (LDV) use, with the mid (base) case scenario assuming 500,000 fuel cell electric vehicles in operation by 2030 and 12 million by 2050 [12]. Based on market analysis, cost projections, and using LDV demand as a basis, a base case buildout scenario for renewable hydrogen production was developed. Within each of the demand scenarios, projections for facility counts were made for 2025, 2030, 2040, and 2050 based off the developed base case demand scenario.

The base case scenario counts for each technology type and analysis year are shown in Table 2. Based on the base case scenario, high-demand, low-demand, high-electrolyzer, high-thermochemical, and high-biomethane cases were also developed. Because the buildout base case represents mid-level transportation end use demand, the buildout high- and low-demand cases represent high- and low-case end use demand. The three following cases, high-electrolyzer, thermochemical, and biomethane, account for a more favorable cost progression for the technology of focus. For example, for the high-electrolyzer scenario, the cost progression of electrolyzer technology is favorable relative to the others. These scenarios are rooted in the growing demand for renewable hydrogen, which is facilitated by the state’s carbon emission reduction goals.

Technology	2025	2030	2040	2050
Solar Electrolysis	4	13	169	265
Wind Electrolysis	1	6	72	113
Thermochemical	1	5	20	30
Dairy Anaerobic Digestion	5	24	28	28
Food Anaerobic Digestion	3	19	21	21
SMR	2	21	51	51

Table 2: Base case scenario counts

Each of the scenarios were built on a variety of assumptions, including: assuming only renewable hydrogen demand (not non-renewable hydrogen), reference facility sizes, and spatial demand distribution following the analysis in the AB 8 report, published by the California Air Resources Board. The reference facility sizes, shown in Table 3, were determined by stakeholder interviews and cost projections [12]. Similarly, it was assumed that the product of anaerobic digestion facilities is biomethane with quality suitable for pipeline distribution. The ancillary SMR facilities were assumed to have the ability to support reformation of pipeline biomethane, which was founded on the base assumption of a 50% share of the biomethane being allocated to renewable hydrogen.

Technology	Facility Size
Thermochemical Conversion	25,000 kg RH_2/day (for commercial pilots) 30,000 kg RH_2/day (through 2030) 150,000 kg RH_2/day (beyond 2030)
Anaerobic Digestion	7,500 kg RH_2 /day
SMR / associated liquefaction facilities	30,000 kg RH_2/day
Electrolyzers	5,000 kg RH_2/day (for commercial pilots) 20,000 kg RH_2/day (for 2030 and beyond)

Table 3: Reference facility sizes used in the analysis

This spatial demand distribution within the AB8 report determined the population centers that were assumed to be transportation demand centers within the analysis. This allowed for the ArcGIS analysis to prioritize proximity to transportation end use applications within the context of feedstock availability. The transportation demand centers, shown as having a high density of hydrogen refueling stations, used in the analysis are shown in Figure 9.

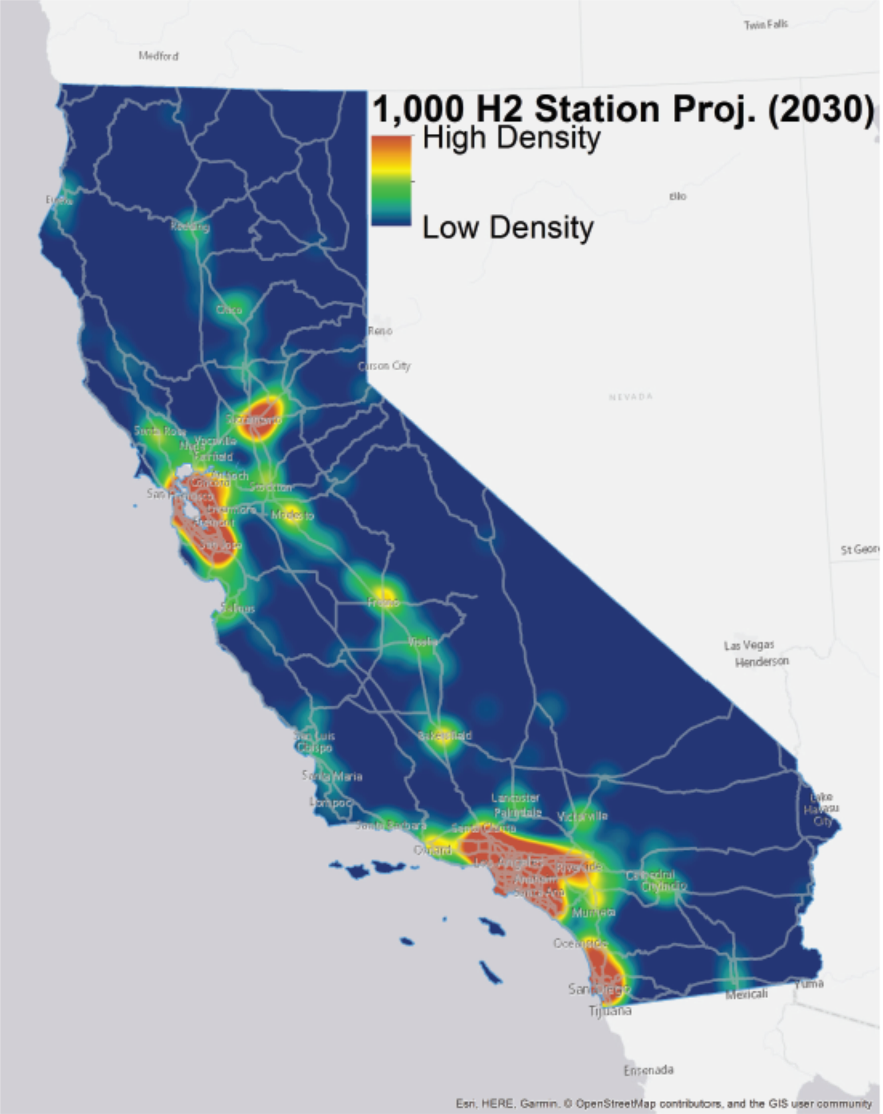

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Figure 9: Primary demand centers for renewable hydrogen use in transportation applications [32]

The development and siting of each of the scenarios demonstrates the uncertainty of which technologies will emerge in the greatest capacities, while demonstrating the feasibility of various buildout sequences. Because the demand for renewable hydrogen will increase in the decades to come, many facilities will need to be constructed. The number of suggested facilities is subject to change based on cost reduction, legislative changes or mandates, market-driven growth, and the cost and availability of feedstock.

6. Task 3 Results: Characterize Cost

Due to many of the technologies being pre-commercial or emerging, cost of implementation is largely based on projection. Assessing the cost at each point within the supply chain is critical to providing justification for buildout of these technologies. To provide context to the geospatial analysis done in this thesis, the projected cost at each time step of the analysis is given based on the work completed under the Roadmap. Learning curve analysis provides a basis of cost projection, and this analysis can be done using either cumulative production or time as the independent variable. Wright's Law states that cost will decrease by a fixed percentage as the cumulative production doubles. This relation is shown in Equation [1], where x_t refers to the cumulative production, x_0 refers to the cumulative production at the starting point, C refers to the cost at each point, and b refers to the positive learning parameter [33].

$$[1] \quad C(x_t) = C(x_0)(\frac{x_t}{x_0})^{-b}$$

Moore's Law, in contrast to Wright's Law, states that cost will decrease exponentially with time, without direct attribution to controllable action such as policy framework, research, and development [34]. The forecasted technology implementation cost in this analysis was completed using Wright's Law, for this reason. To forecast technology cost, a learning rate to apply was selected based on an optimistic and a conservative estimate. Based on a study considering 22 industrial sectors and their associated learning rates, a conservative rate of 10% and an optimistic rate of 20% was selected for use in the various scenarios within the analysis [12]. The distribution of learning rates, which informed the basis of projection used in this analysis, is shown in Figure 10.

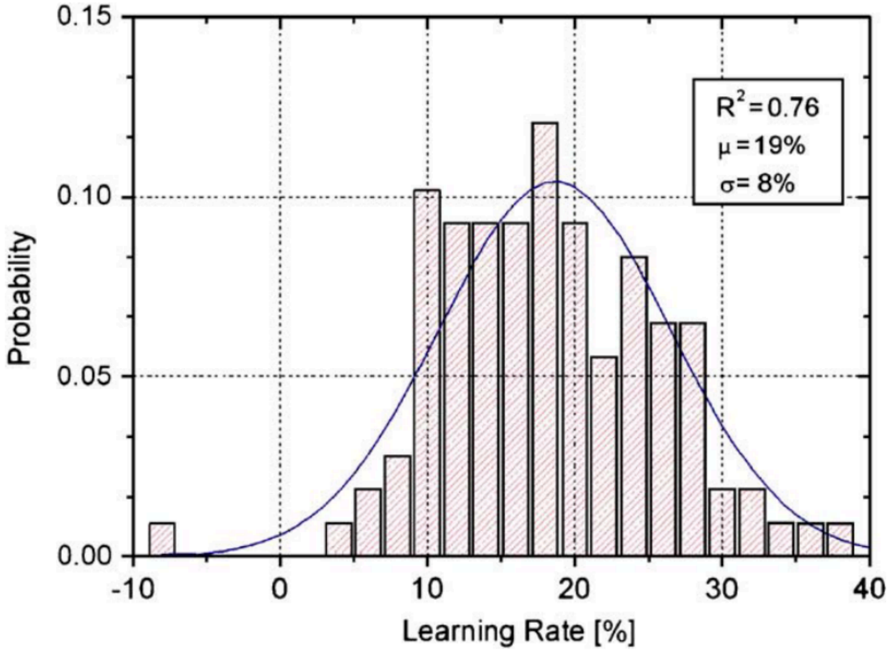

Figure 10: Distribution of learning curves fit to a normal curve used to inform the analysis [33]

When applied to a capital cost assessment based on feedback from industry stakeholders, implementation costs for each technology were produced and used in the analysis. The projection is shown in Figure 11.

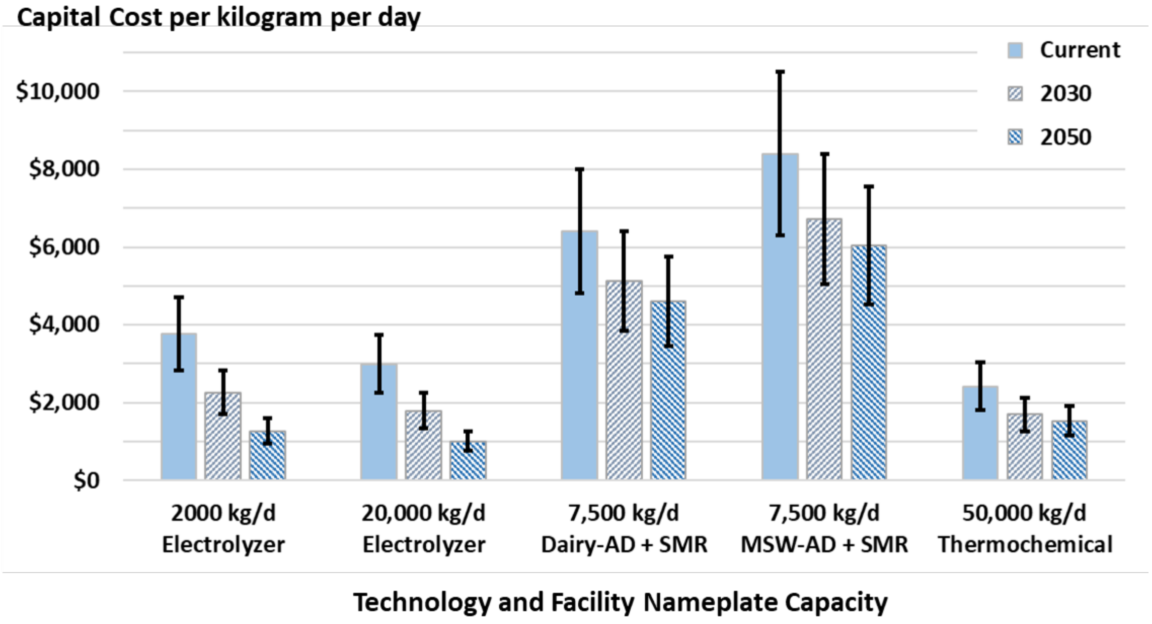

Figure 11: Capital cost per unit of renewable hydrogen production capacity [12]

The conversion efficiency related to each technology is critical to the amount of renewable hydrogen produced. The conversion efficiency, when applied to the cost of the feedstock, indicates the actual amount of renewable hydrogen produced per unit of feedstock. This, when coupled with capital cost and operation and maintenance costs, indicates the total cost of production for each technology. The technology characterization, including each of these conversion efficiency values and operation and maintenance costs, is shown in Table 6.

Technology	Electricity Use/ Conversion Efficiency, based on LHV (Current)	Operation and Maintenance Costs (Current)	Conversion Efficiency, based on LHV (Future)	Operation and Maintenance Costs (Future)
Electrolyzer	54.6 kWh/kg	1.75-3% of Capital Cost	50.2 kWh/kg	Fixed percentage
Anaerobic Digestion, Covered Lagoon	38%	4% of capital cost (fixed) + \$1.25/MMBTU (variable)	42%	Fixed percentage and variable cost
Anaerobic Digestion, Above-Ground	50%	4% of capital cost (fixed) + \$2.50/MMBTU (variable)	55%	Fixed percentage and variable cost
Gasifier	54%	\$40/kW-yr (fixed) +\$6/kW-yr (variable)	62%	\$26/kW-yr (fixed)+ \$4/kW-yr (variable)

Table 4: Technology characterization of various production pathways [12]

Lastly, the cost of feedstock for each technology was determined. Thermochemical feedstock was determined using the Billion Ton Report data, which reports availability of biomass based on harvest and recovery costs. These data were coupled with forestry data from CalFire, which provides greater detail surrounding the type and availability of forest trimmings with potential use in thermochemical conversion. The availability of agricultural residue and forestry biomass for thermochemical conversion, shown in prices of \$30 and \$100/dry ton, is shown in Figure 12. Within this analysis, dedicated energy crops were not considered, as they have yet to become widely adopted.

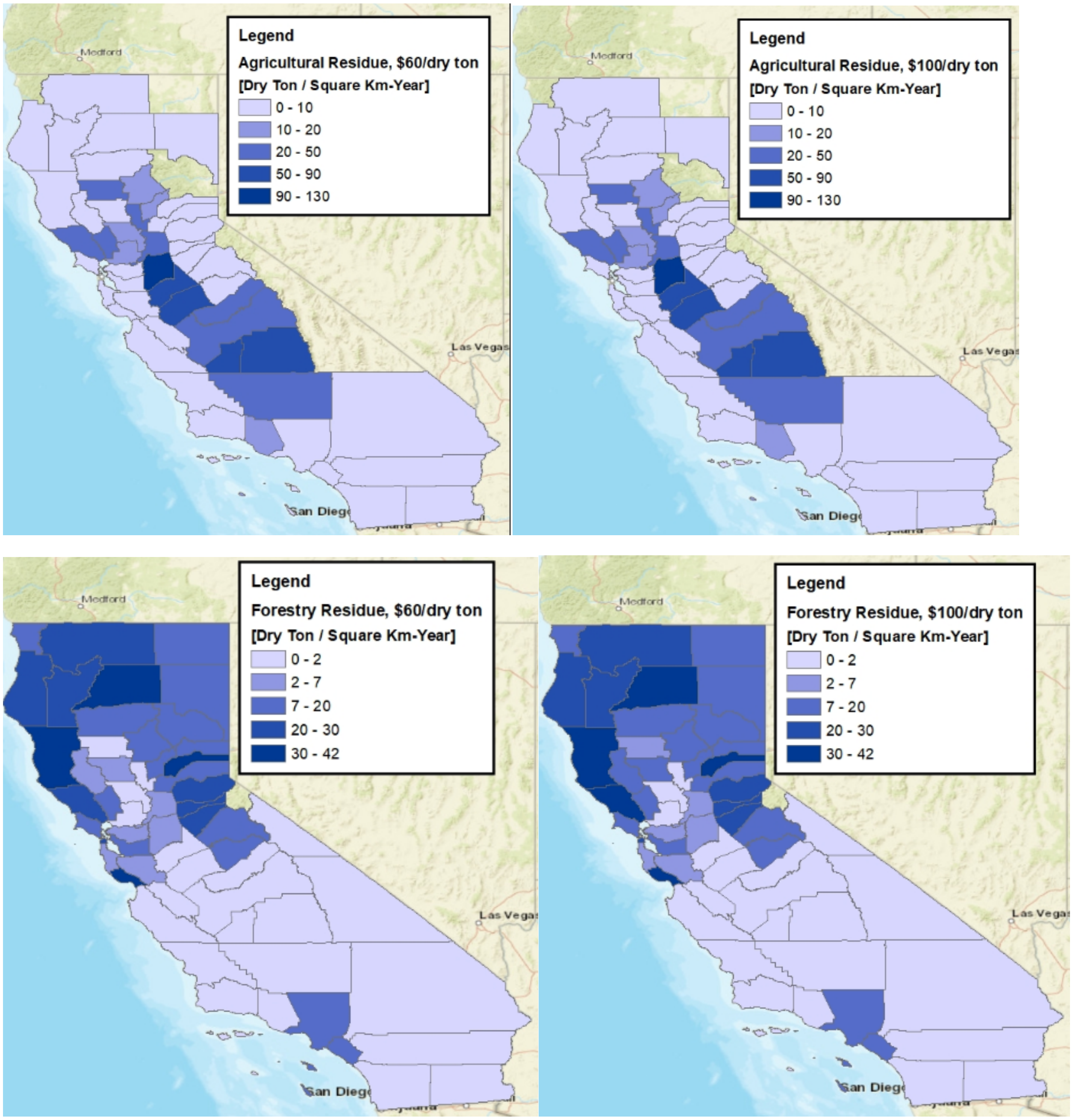

Figure 12: Biomass (agricultural residue and forestry) available at two price points statewide [21][20]

For anerobic digestion, dairy manure and landfill gas were assessed for availability. To assess the availability of dairy manure, the number of milking cows statewide and their associated waste amounts were spatially resolved. Similarly, the organic fraction of municipal solid waste

(OFMSW) was considered for anaerobic digestion. This was obtained using the Billion Ton Report, and these locations were primarily situated within high population centers (cities). The availability of dairy manure throughout the state is shown in Figure 13.

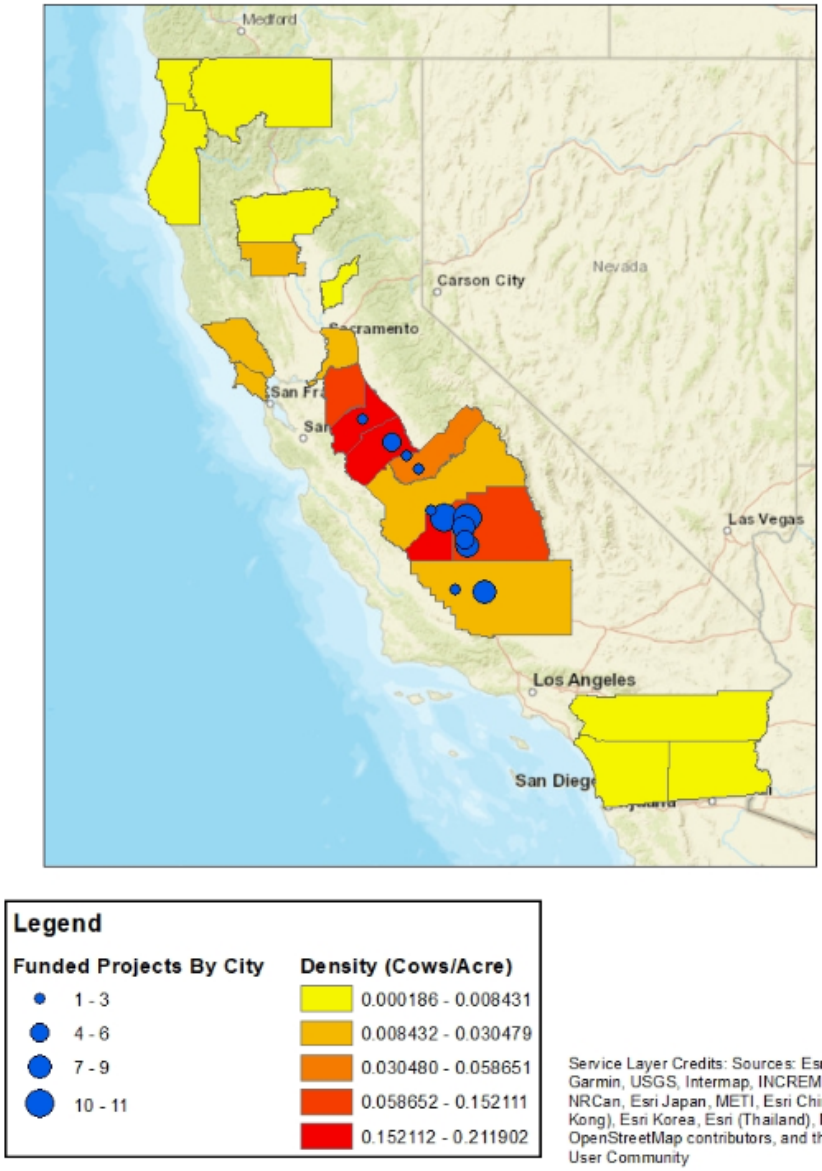

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Figure 13: Dairy manure feedstock availability for use in anaerobic digestion [35], [36]

The renewable power feedstock used in electrolysis was assessed based on solar and wind availability across the state. For wind resource, the availability was determined using the wind power class (WPC) scale, which characterizes the power produced by average daily onshore wind speed at 50 meters of height. This is shown in Figure 14 and existing Renewable Portfolio Standard (RPS) wind projects are shown to illustrate the current areas of wind power development. Similarly, solar availability was determined using the average direct normal irradiation (DNI) at a given location. This illustrates how much solar irradiation an area receives on average throughout the year. Solar DNI is shown in Figure 15 along with the current RPS solar projects.

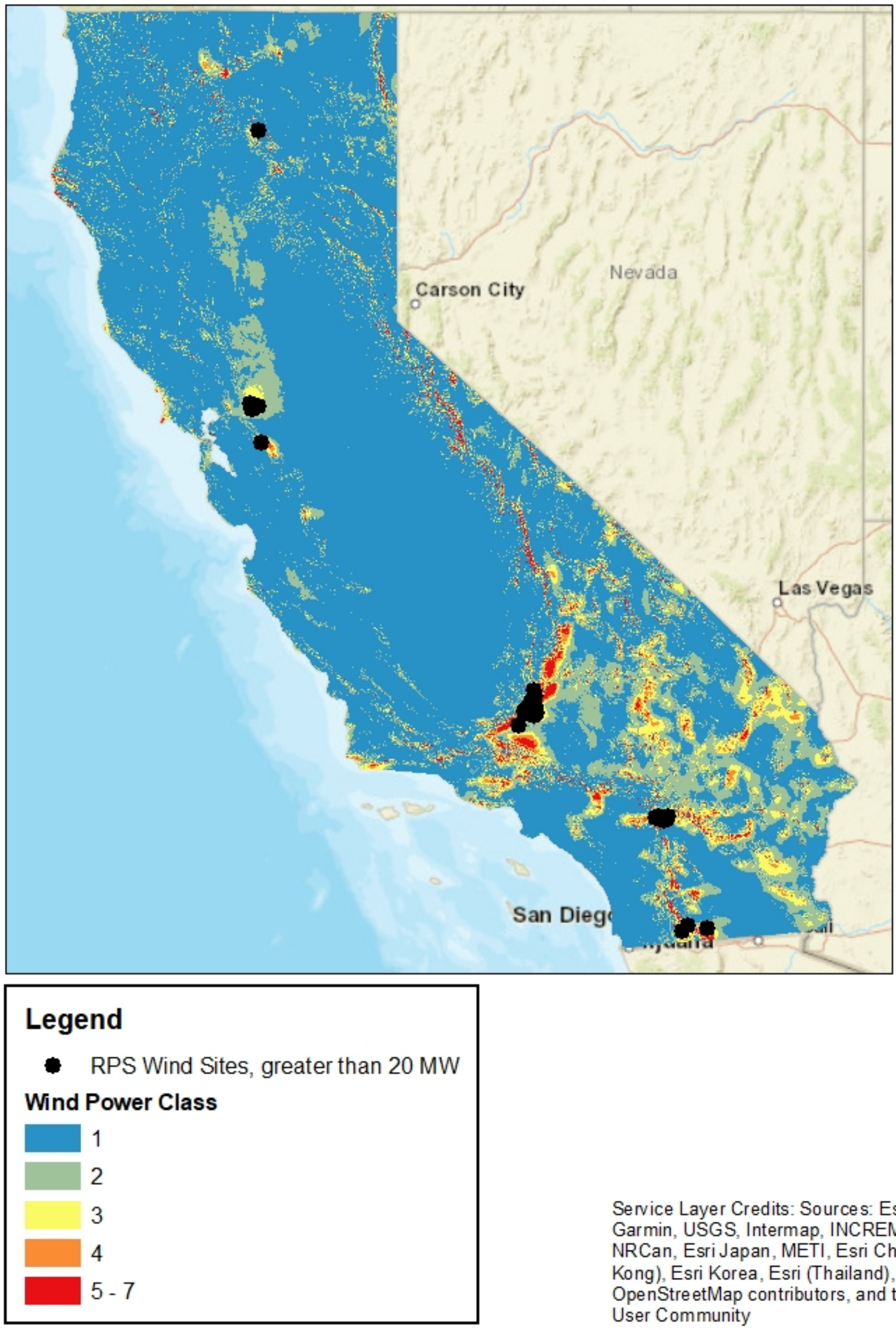

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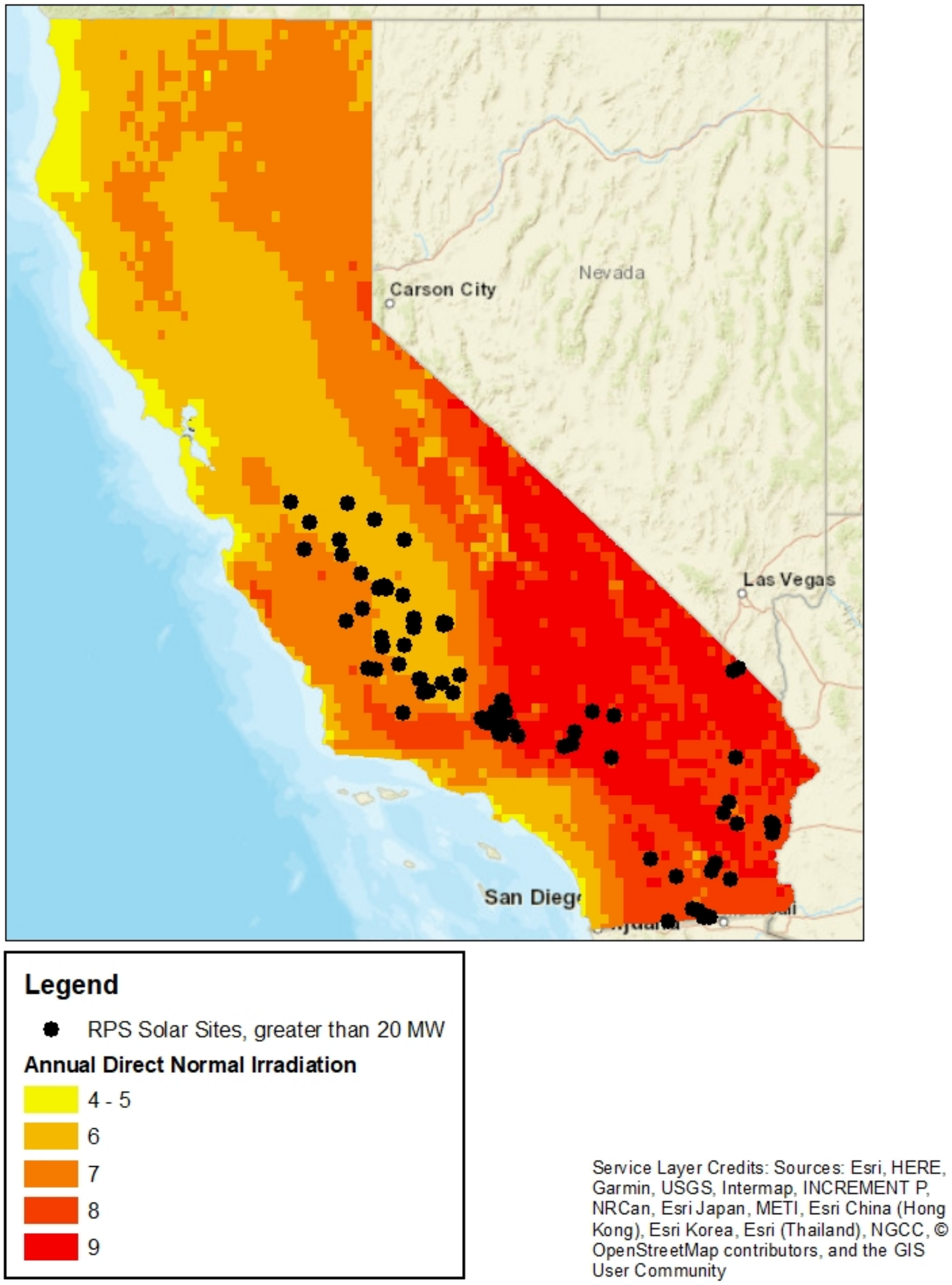
Figure 14: Onshore wind availability statewide[19]



Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, © OpenStreetMap contributors, and the GIS User Community

Figure 15: Solar resource availability statewide [18]

The California Public Utility Commission (CPUC)'s RESOLVE model provides assessment of various power generation methods in order to inform key personnel of new resources that will meet climate policy objectives. The information within RESOLVE provides a basis for forecasting electricity costs at new wind and solar power generation locations. Using the information outlined in RESOLVE and the Lazard Levelized Cost of Energy (LCOE) Report, a projected cost for renewable power was obtained and used in the analysis [12], [37]. The cost projection curve used in this analysis is shown in Figure 16.

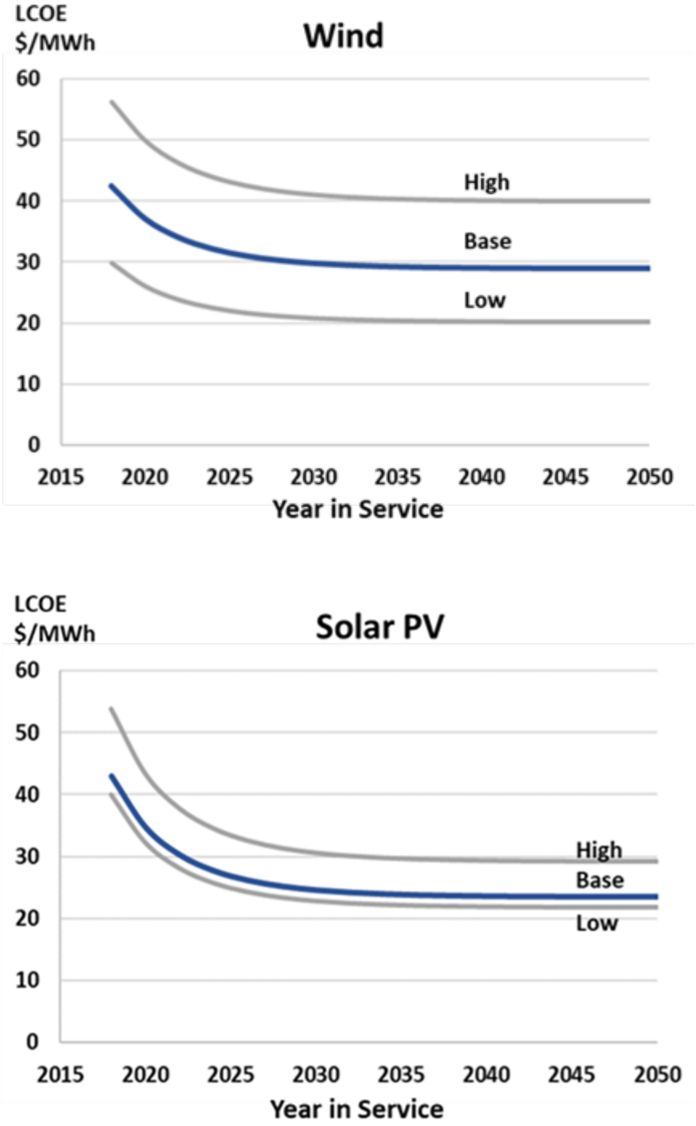


Figure 16: Cost projections for wind (above) and solar (below) renewable power [12]

The cost and availability of renewable power feedstock is important when considering the feasibility of project development, as this information will affect profitability of electrolyzer projects in the decades to come. For all of the technologies, capital cost remains an inhibitor to widespread adoption. Therefore, it is necessary to consider the appropriate cost projections in accordance with the geospatial analysis of renewable hydrogen production potential.

7. Task 4 Results: Integrate Hydrogen Delivery

To evaluate the various renewable hydrogen production methods, the supply chain and delivery costs must be examined and integrated into the analysis framework. Renewable hydrogen for transportation use is most commonly delivered via cryogenic liquid tanker trucks and compressed gas trucks. In the future, hydrogen will likely be directly injected into either existing gas transmission pipelines or dedicated hydrogen pipelines. Injection of hydrogen into the natural gas pipeline will require system-by-system analysis to determine appropriate gas blends, leakages, and extraction points, and an extensive dedicated hydrogen pipeline network will need to be constructed in order to serve the growing demand [38][12]. For these reasons, pipeline delivery of hydrogen was excluded from this analysis. Figure 17 shows the two primary delivery chain configurations used in this analysis. It is likely that both configurations will remain in use in the decades to come [39].

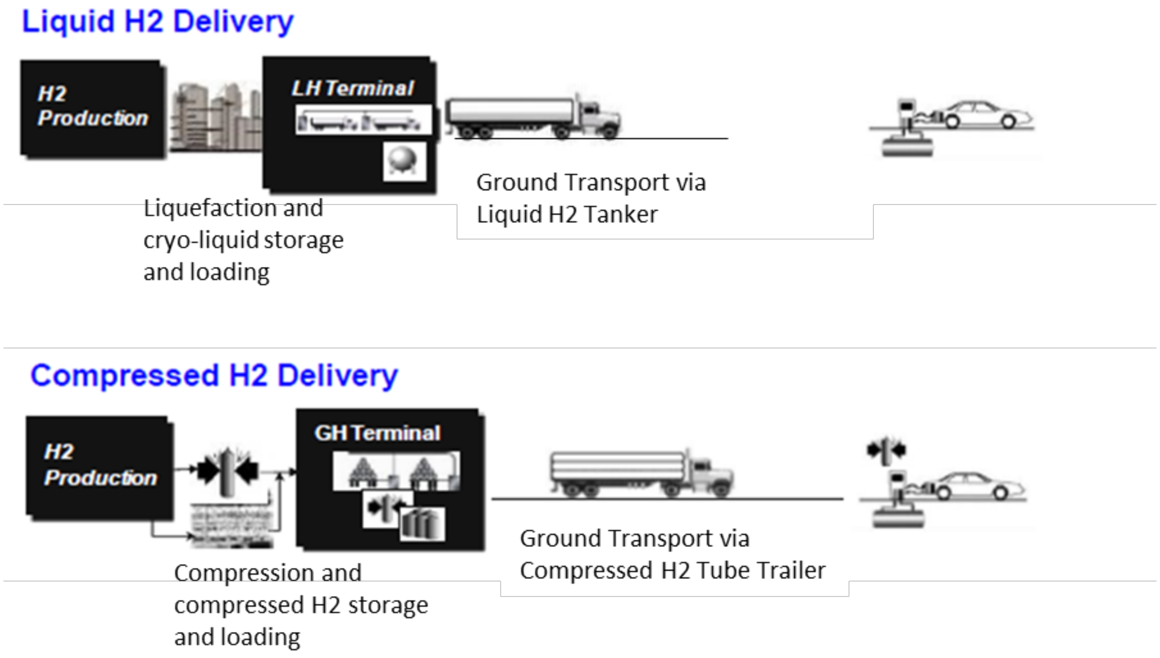


Figure 17: Two primary pathways for renewable hydrogen delivery [12]

HDSAM, a model produced by Argonne National Lab, provides a detailed supply chain cost per kilogram of hydrogen dispensed, based on station size, utilization, and configuration. For the near term, it was assumed that the market volume was low, for 2025, it was assumed medium volume, and for 2030 and beyond it was assumed to be high volume. Similarly, the station sizes were assumed to have increased from 300 kg/day in the near term to 1500 kg/day by 2050, with the utilization of the stations increasing from 40% to 80% over the same time frame. Using these input data, it was projected that the cost of gaseous and liquified hydrogen will reduce from the current value of around $16.00 per dispensed kg to about $4.00 per dispensed kg by the year 2050 [12]. This will allow for the renewable hydrogen market to emerge and become competitive with that of gasoline. These supply chain (plant to dispenser) cost data for both gaseous and liquified hydrogen are shown in Figure 18. In the figure, HRS refers to the hydrogen refueling station used to dispense fuel to the customer.

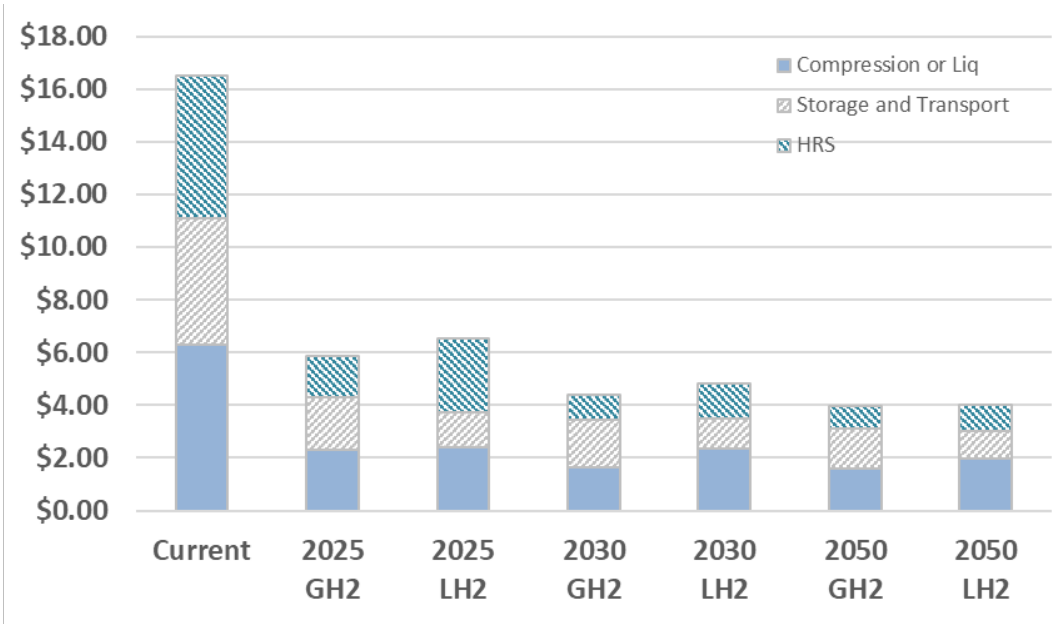


Figure 18: Delivery cost projections, based on HDSAM definitions [12]

8. Task 5 Results: Buildout Plan

The analysis produced various spatial and temporal build-out plans, dependent on adoption of each production technology and demand scenario. The results are presented for each scenario, with particular detail given to the 2030 (mid-range) spatial detail. The results for the siting of locations for the base (mid demand) case are shown in Figures 19 and 20.

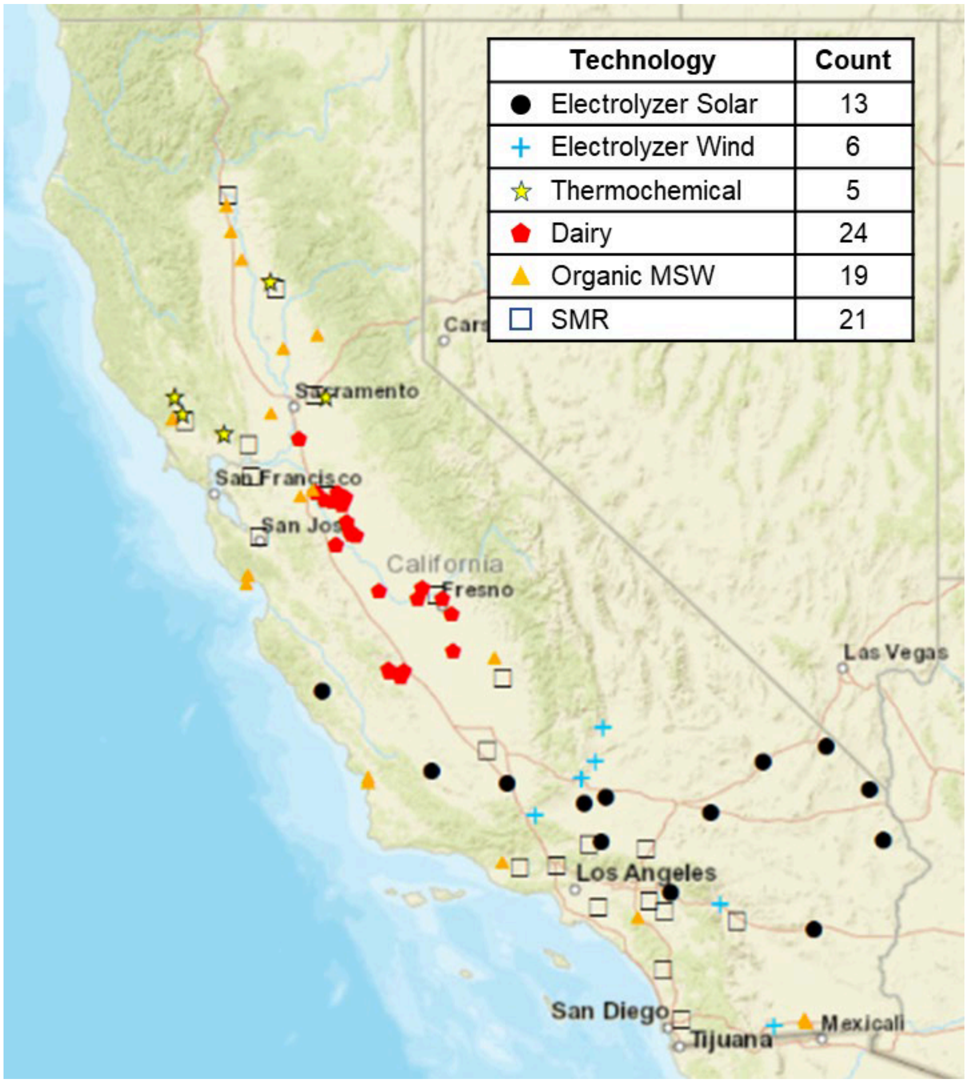
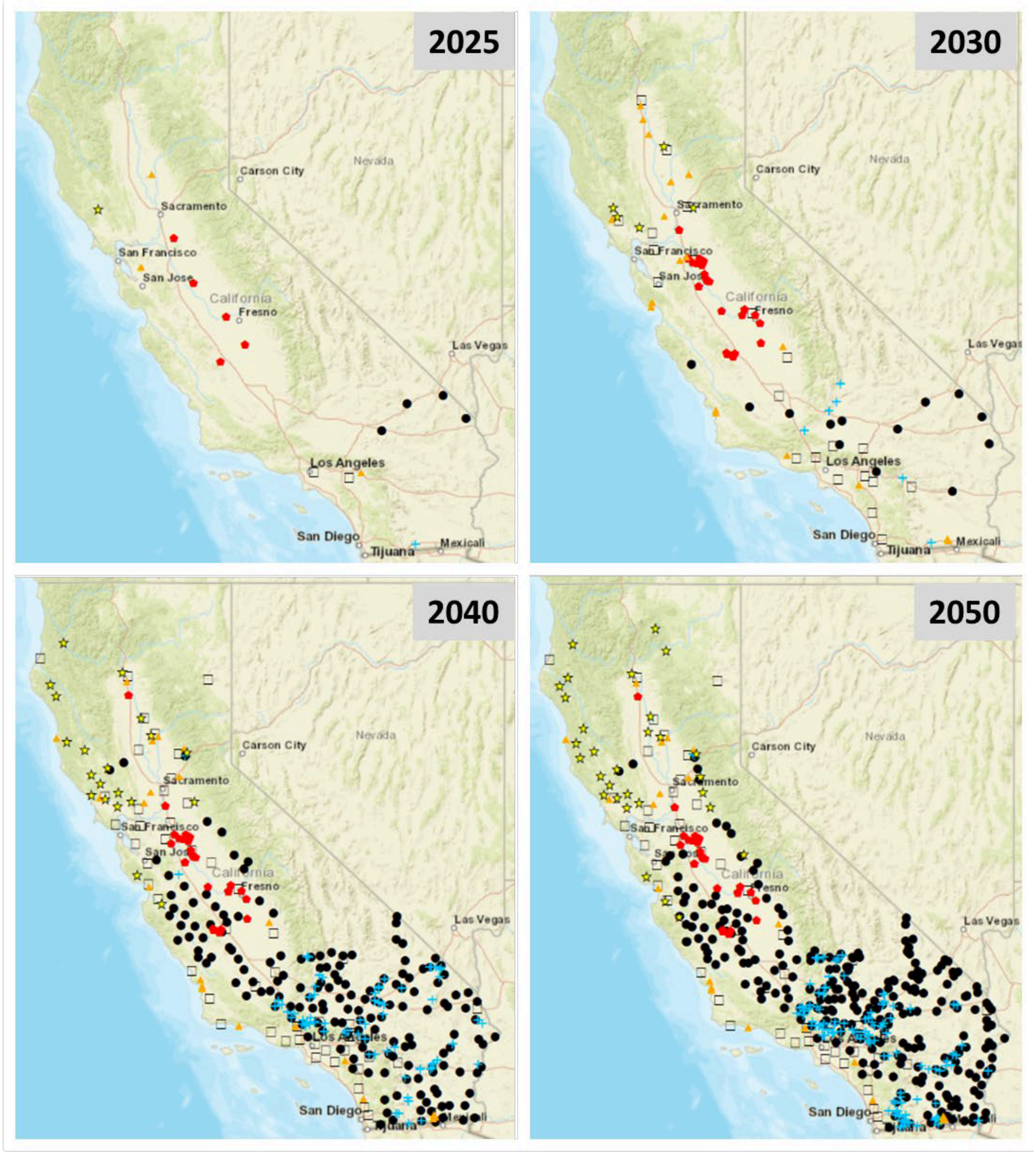


Figure 19: 2030 base case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	4	13	169	265
+ Electrolyzer Wind	1	6	72	113
☆ Thermochemical	1	5	20	30
⬟ Dairy	5	24	28	28
▲ Organic MSW	3	19	21	21
☐ SMR	2	21	51	51

Figure 20: Base case spatial buildout progression from 2025-2050

The siting results for the high demand scenario are shown in Figures 21 and 22.

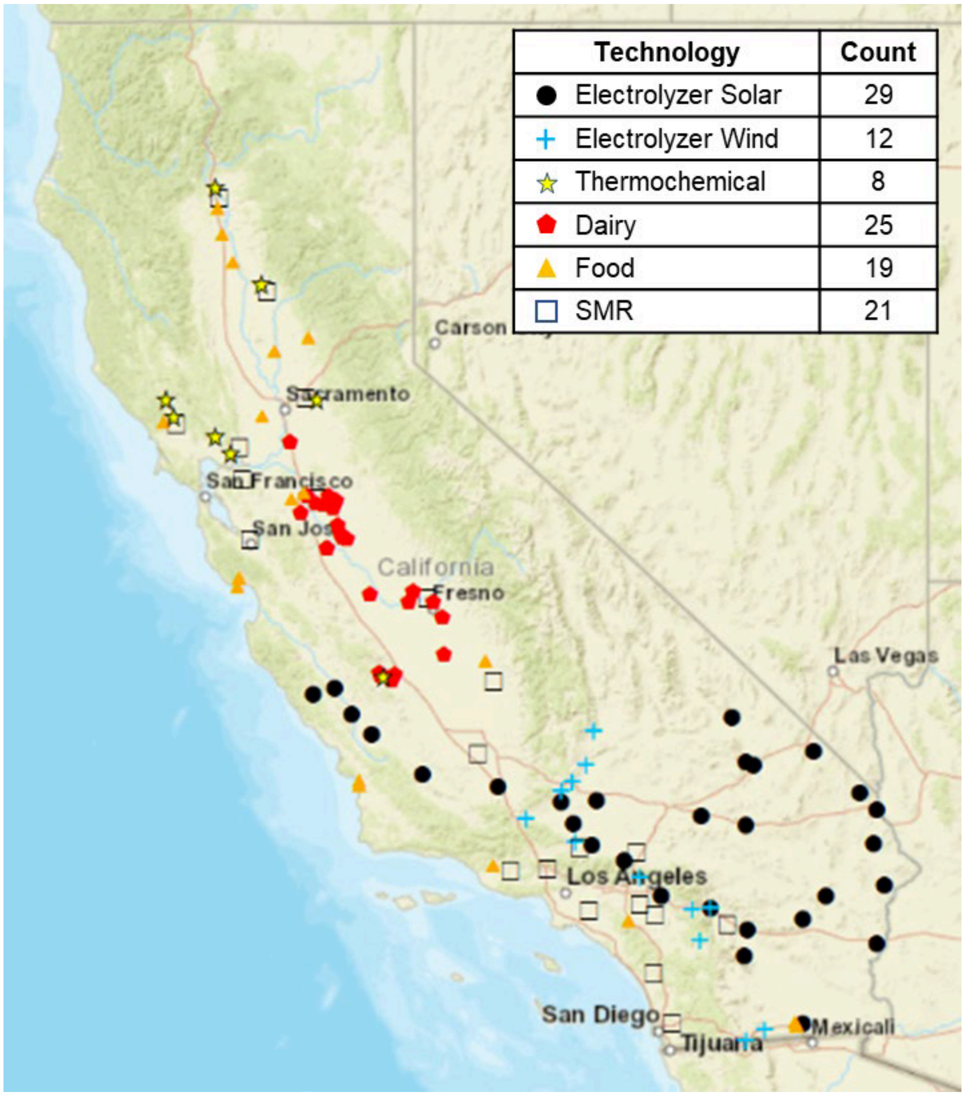
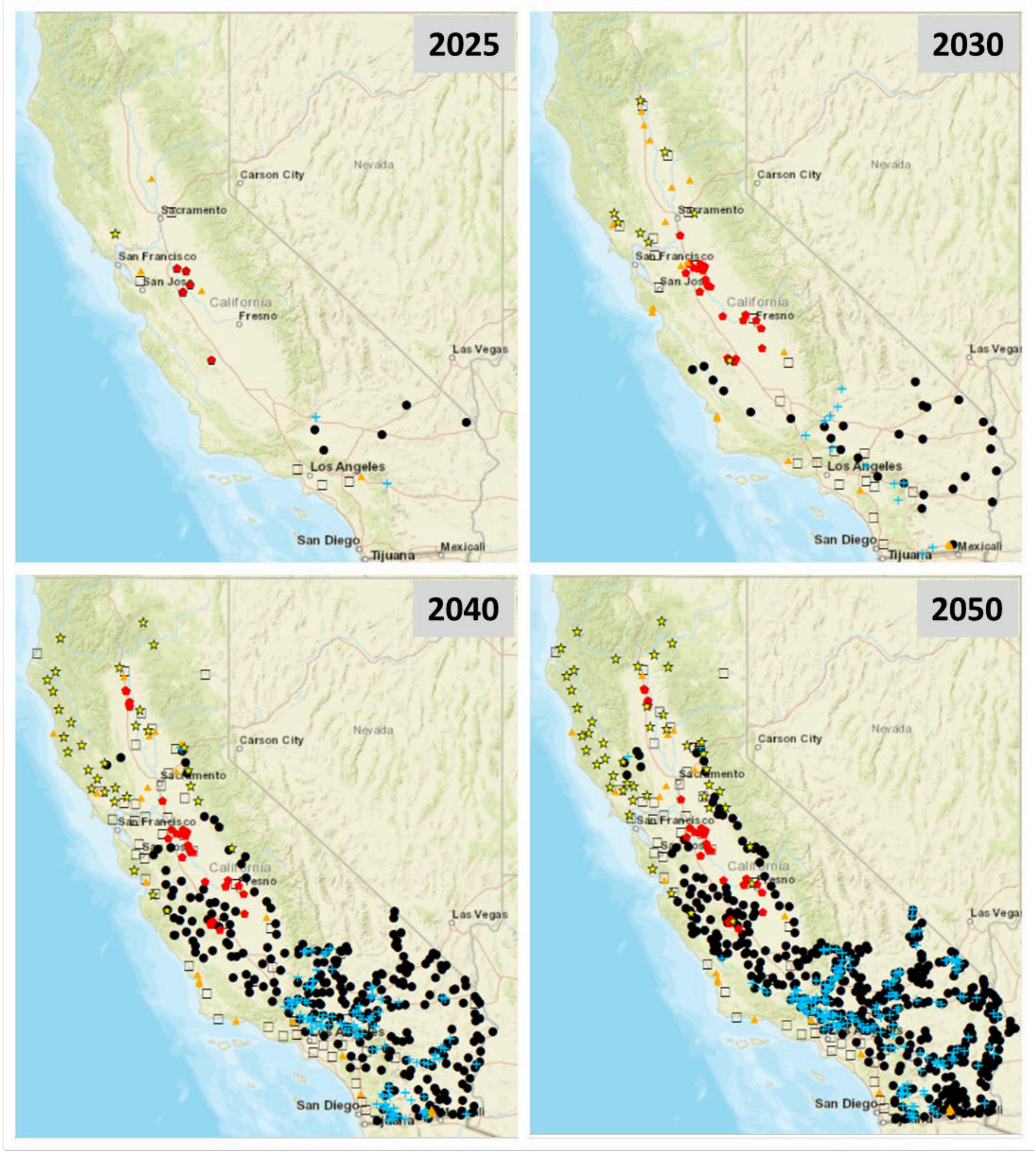


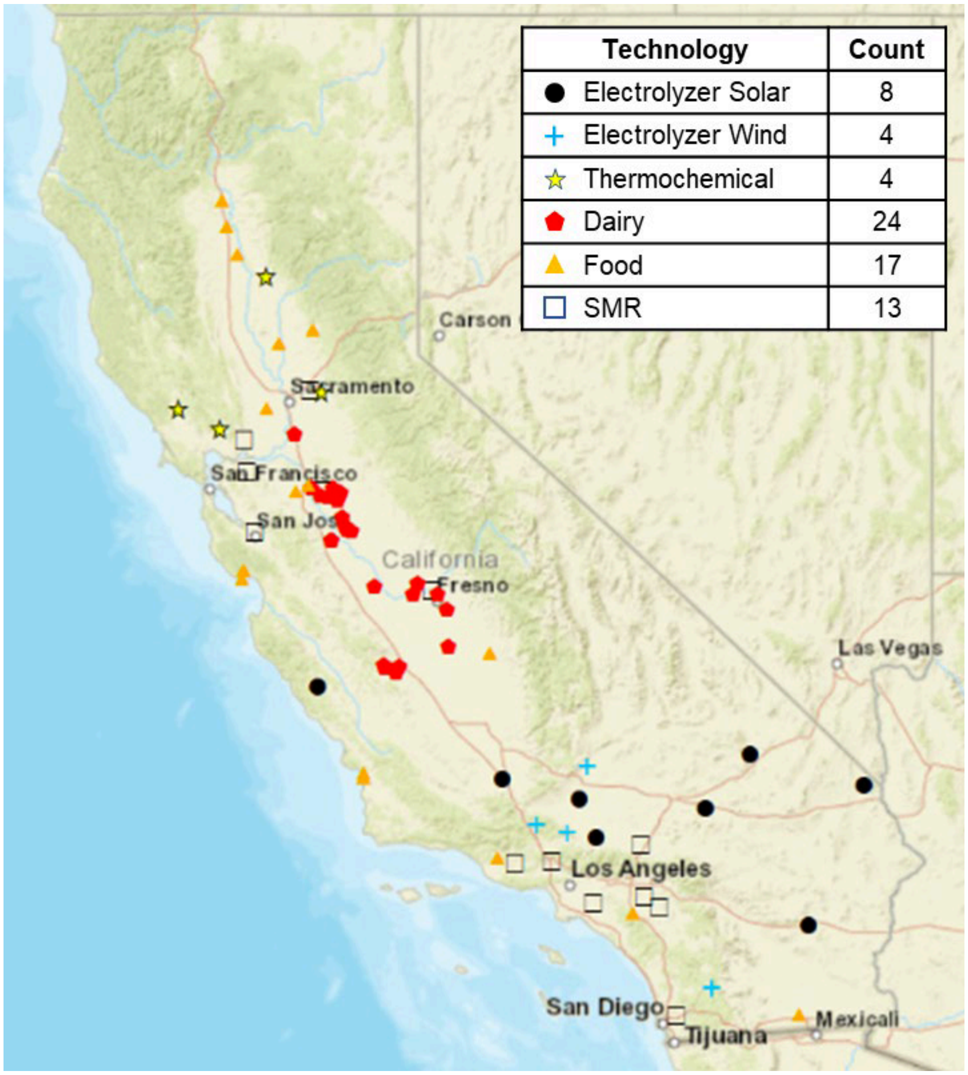
Figure 21: 2030 high demand case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	5	29	265	435
+ Electrolyzer Wind	2	12	114	186
☆ Thermochemical	1	8	31	47
⬟ Dairy	6	25	32	32
▲ Organic MSW	4	19	21	21
□ SMR	5	21	54	54

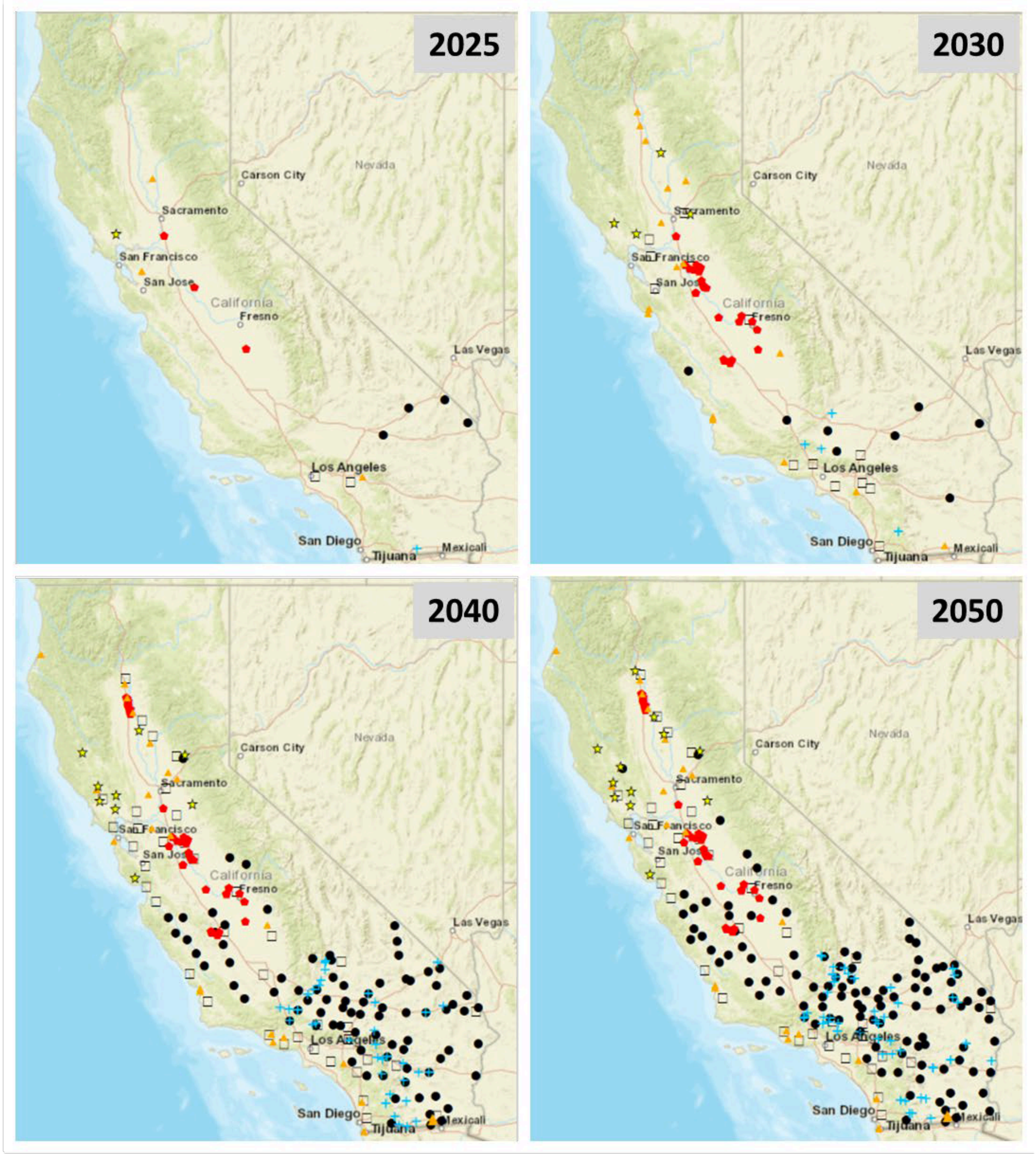
Figure 22: High demand case spatial buildout progression 2025-2050

The siting results for the low demand scenario are shown in Figures 23 and 24.



Technology	Count
● Electrolyzer Solar	8
+ Electrolyzer Wind	4
☆ Thermochemical	4
⬟ Dairy	24
▲ Food	17
☐ SMR	13

Figure 23: 2030 low demand case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	4	8	83	110
+ Electrolyzer Wind	1	4	36	47
☆ Thermochemical	1	4	12	14
⬟ Dairy	2	24	33	33
▲ Organic MSW	0	17	24	24
□ SMR	1	13	39	39

Figure 24: Low demand case spatial buildout progression 2025-2050

The siting results for the high thermochemical buildout scenario are shown in Figures 25 and 26.

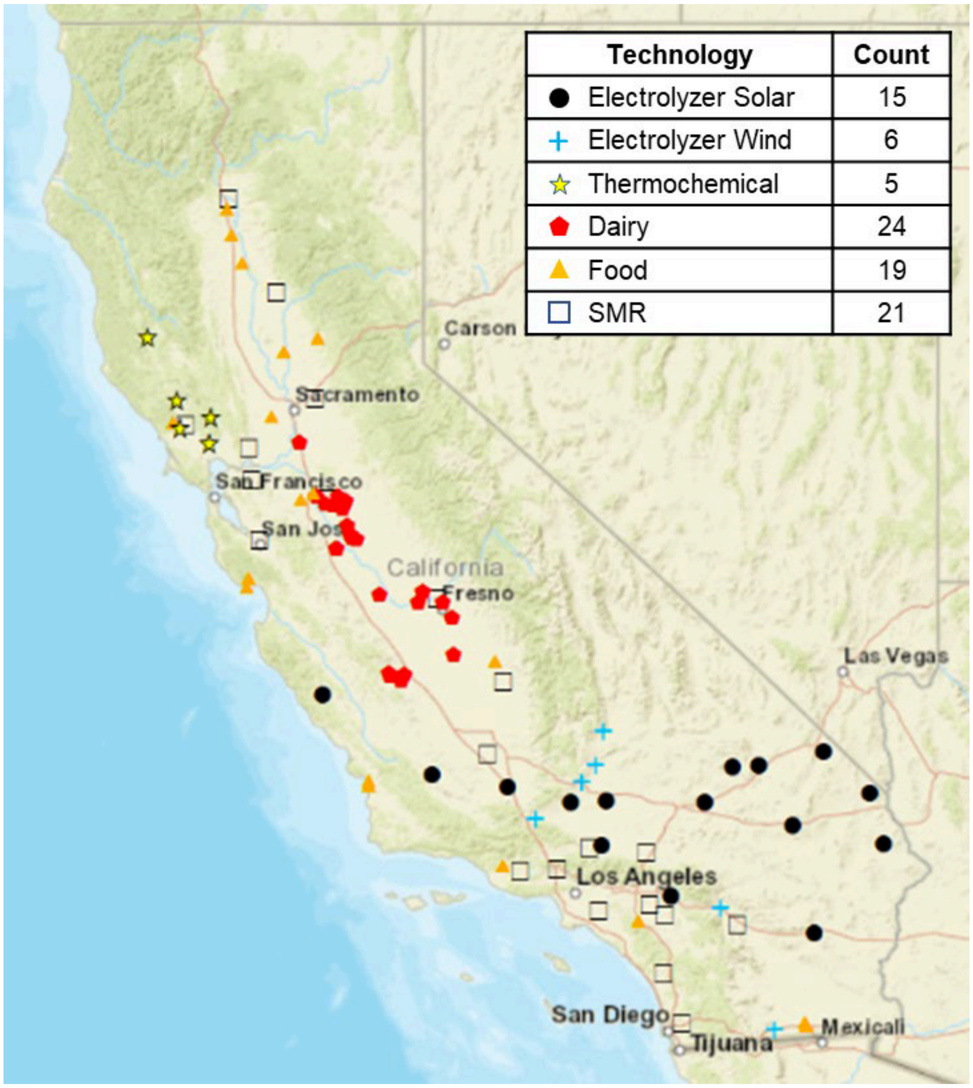
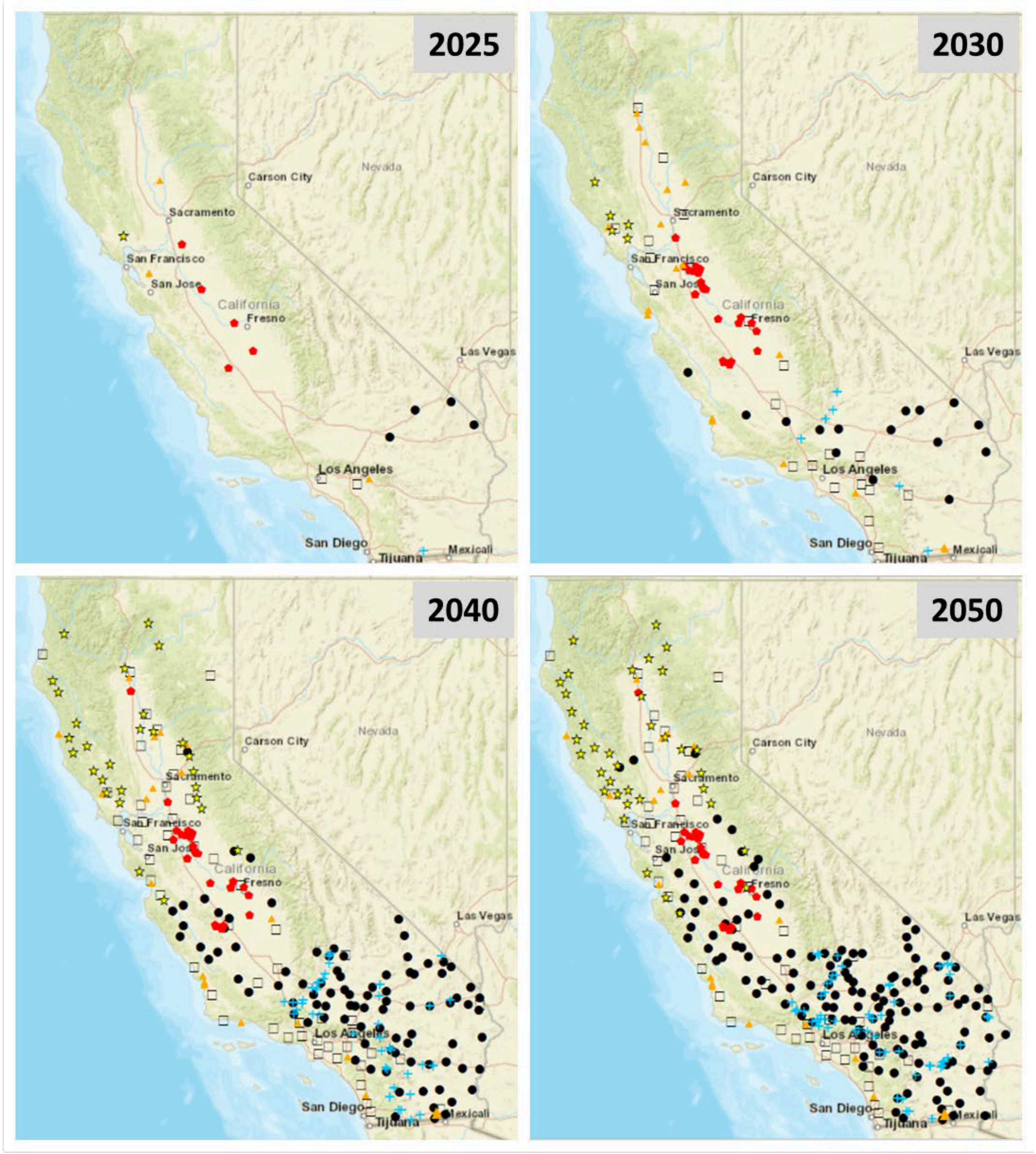


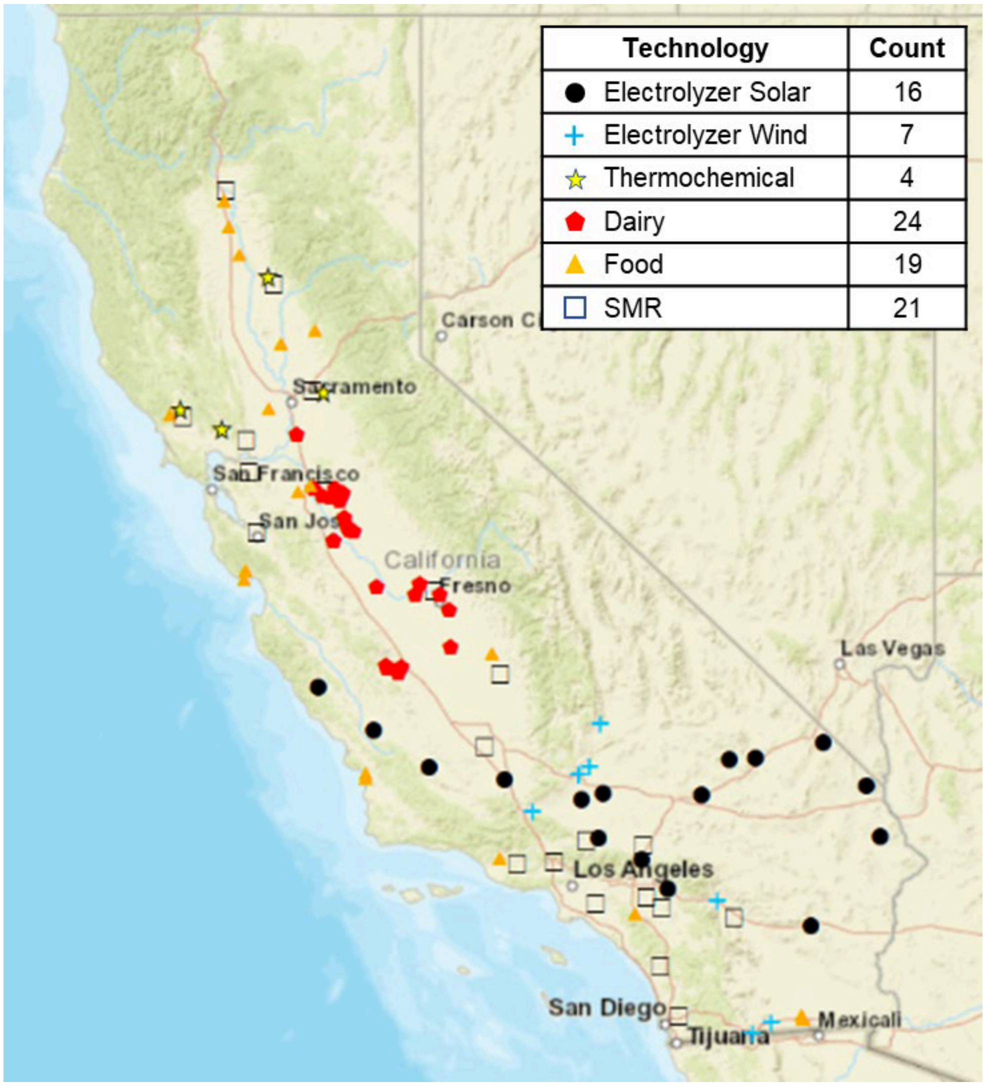
Figure 25: 2030 high thermochemical case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	4	15	92	141
+ Electrolyzer Wind	1	6	40	60
☆ Thermochemical	1	5	28	41
⬟ Dairy	5	24	28	28
▲ Organic MSW	3	19	21	21
☐ SMR	2	21	51	51

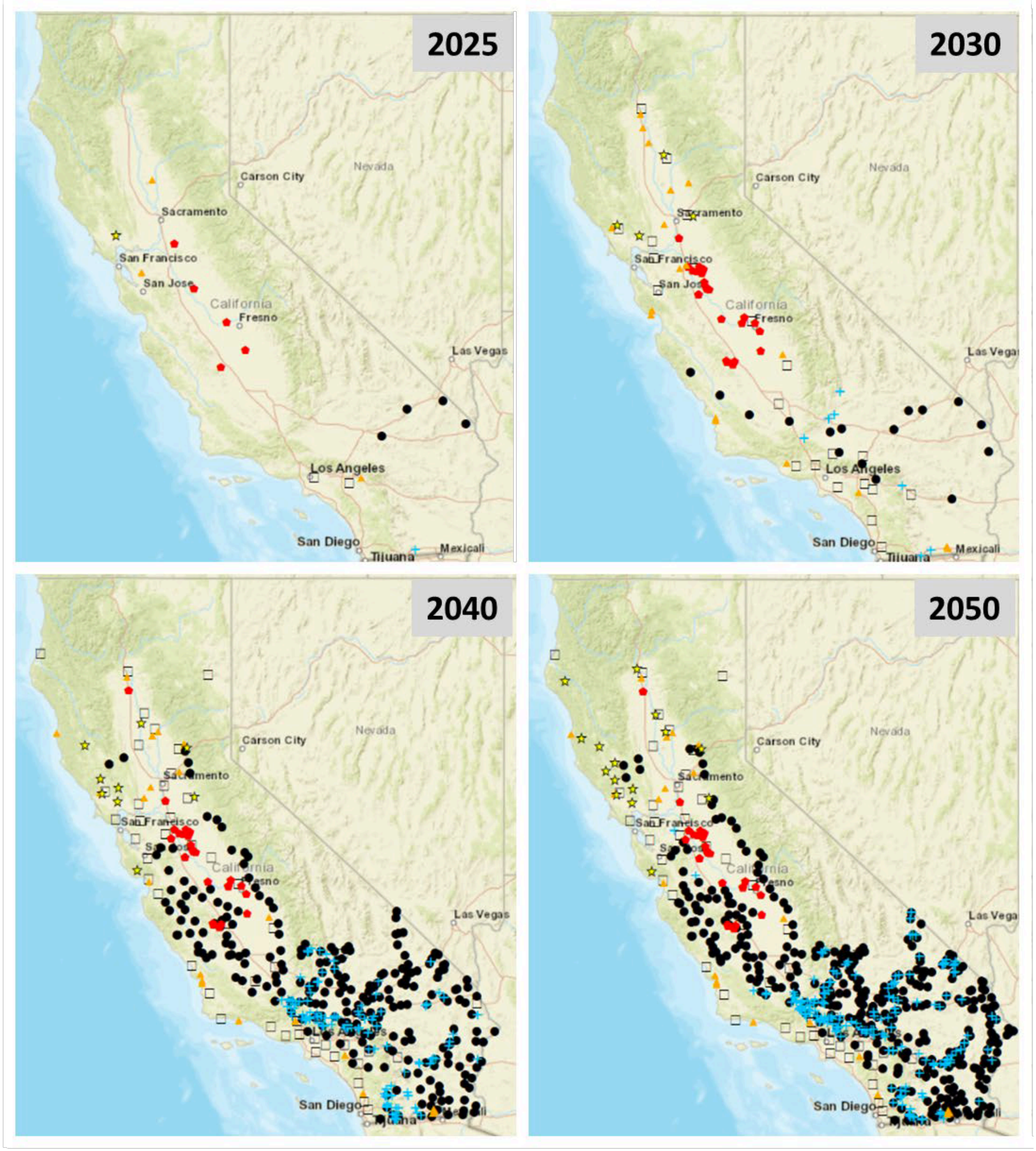
Figure 26: High thermochemical case spatial buildout progression 2025-2050

The siting results for the high electrolyzer buildout scenario are shown in Figures 27 and 28.



Technology	Count
● Electrolyzer Solar	16
+ Electrolyzer Wind	7
☆ Thermochemical	4
⬟ Dairy	24
▲ Food	19
☐ SMR	21

Figure 27: 2030 high electrolyzer case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	4	16	249	390
+ Electrolyzer Wind	1	7	106	170
☆ Thermochemical	1	4	12	17
⬟ Dairy	5	24	28	28
▲ Organic MSW	3	19	21	21
□ SMR	2	21	51	51

Figure 28: High electrolyzer case spatial buildout progression 2025-2050

The siting results for the high electrolyzer buildout scenario are shown in Figures 29 and 30.

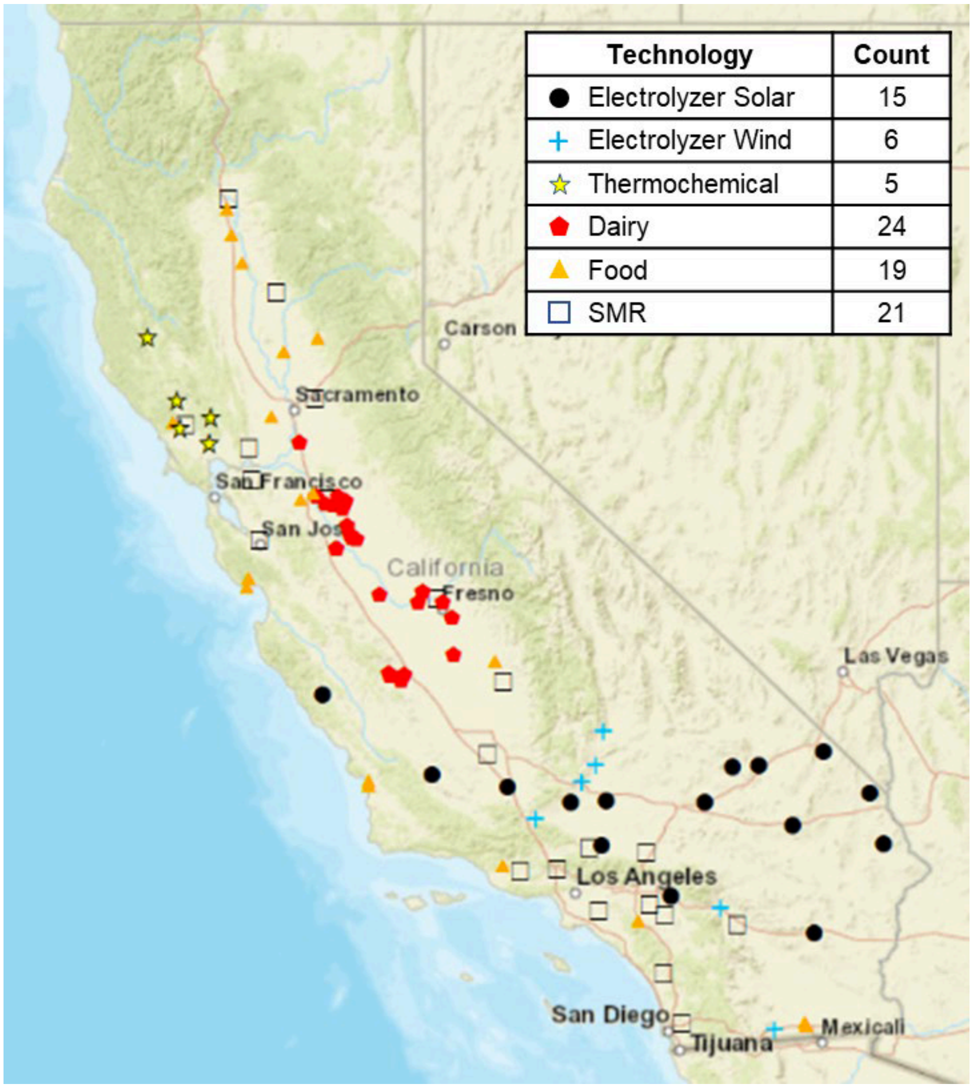
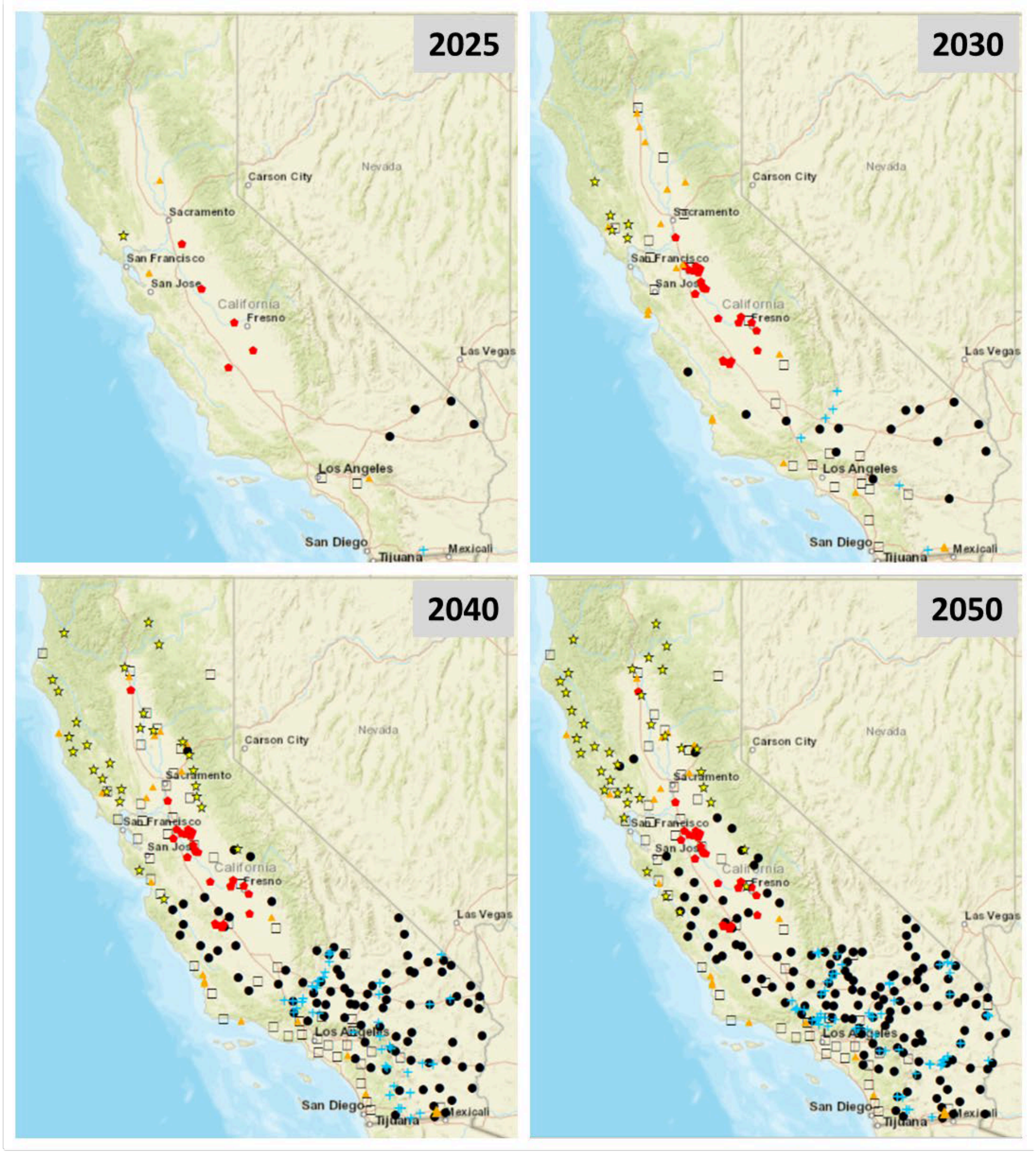


Figure 29: 2030 high anaerobic digestion case spatial detail



Technology Count by Year	2025	2030	2040	2050
● Electrolyzer Solar	4	15	92	141
+ Electrolyzer Wind	1	6	40	60
☆ Thermochemical	1	5	28	41
⬟ Dairy	5	24	28	28
▲ Organic MSW	3	19	21	21
☐ SMR	2	21	51	51

Figure 30: High anaerobic digestion case spatial buildout progression 2025-2050

In each case, the buildout progression follows a similar pattern, which reflects the highest resource area for each technology type as well as the proximity to critical existing infrastructure. For wind- and solar-powered electrolyzers, these sites are primarily situated in the southeastern, desert corner of the state. Thermochemical production locations are sited nearest forest cover in the northern portion of the state. Dairy manure anaerobic digestion is located within the dairy locations in the Central Valley, and organic MSW anaerobic digestion is located nearest high population centers (cities). Similarly, SMR sites are also located near demand centers. In the earlier years and for the low-demand cases, the most optimal sites are chosen. For each increase in demand and for each subsequent modeling year, it becomes necessary to site locations in areas further from distribution infrastructure and in areas with less optimal resource availability in order to meet the steep growing demand for production.

In each scenario, it is evident that significant buildout will be required to meet climate objective and potential market demands. However, given the projected cost reduction and transportation end use demand, it is likely that the buildout efforts will be supported. Similarly, it is likely that the buildout efforts will continue to be supported by state and local policy efforts. Despite the vastness of the renewable hydrogen production technology development presented in these scenarios, it is reasonable to expect that this level of buildout will be needed and utilized in decades to come.

9. Summary

In this thesis, various renewable hydrogen production methods were assessed for spatial and temporal buildout feasibility based on cost projections and technology characteristics. This was accomplished by defining the feedstock, cost, performance, and siting requirements for each technology. To this end, an analysis of solar, wind, high- and low-moisture content organics was conducted to determine the locations with the highest resource. Cost projections for development of each technology as well as delivery cost were also provided as context and justification for project development. Next, various scenarios, each with different technological emphasis, were developed to create a temporal, numerical buildout strategy consistent with the adoption feasibility of each technology. Each scenario provides an increasing number of each technology type for the years 2025, 2030, 2040, and 2050. Using these scenarios, ArcGIS was used to geospatially resolve these counts such that available feedstock for each technology was supplied most efficiently to the sited production location. Within the geospatial resolution, many exclusions were made, including accounting for terrain not suitable for development, proximity to relevant existing transportation infrastructure, and community impacts. The results of the geospatial analysis were presented as a spatial and temporal buildout plan for each scenario.

10. Conclusions

1. **Feedstock availability is largely region-specific and can support large buildout counts for each technology type.**

   In this analysis, it is evident that feedstock availability is a critical driver for site selection. However, it is crucial to determine whether large count numbers for later years (2030 and beyond) will be supported by the amount of existing and available feedstock in those years. This analysis suggests that this is plausible; within the location-allocation in ArcGIS, the required amount of feedstock for each technology type was successfully allocated to each site in later years. If feedstock was unavailable within the determined service area, the site would not be able to be located by the analysis and the desired count of located facilities would not be achieved. Because feedstock is available to support large numbers of renewable hydrogen production locations for transportation applications, it is reasonable to assume feedstock is available for the development of dedicated renewable hydrogen production faculties for energy storage applications in addition to those built solely for transportation applications. This is an encouraging finding, as it validates the ability to vastly expand the renewable hydrogen production network for both transportation uses and other energy services.

In the future, to advance and deepen the efforts of this work, a closer study of feedstock availability using more specific exclusion criteria would be beneficial. Specifically, accessing county- and city-level land use data would give greater depth and understanding to the available terrain and undevelopable space. With a more robust, detailed feedstock dataset, the resolution of the findings for each scenario can be increased, allowing for more tangible site recommendations to be made to policymakers, planners, and investors. The ability to exclude locations that are inaccessible and include locations mistakenly excluded from current feedstock estimations would give a more meaningful estimation of the amount of renewable hydrogen production technology that could be supported within the state.

2. **With continued policy framework and state support, the renewable hydrogen production sector can become fully self-sufficient in the decades to come.**

In each scenario, many facilities are sited in order to meet the projected market demand as well as adhere to the climate objectives outlined by the state. However, for renewable hydrogen to become competitive with existing transportation fuels, it must compete in price with gasoline—around $4 per gallon or per kilogram. Based on Wright's Law, the cost of renewable hydrogen by each production method decreases as production capacity increases. This will render these technologies financially feasible. As the renewable hydrogen production market emerges, the rollout of hydrogen refueling stations will simultaneously continue to advance. To this end, as shown using HDSAM data, the combined cost of compression, liquification, transportation, and refueling processes will decrease from the current cost of about $17/kg dispensed to the target of $4/kg dispensed around the year 2030. These cost declinations will encourage higher rates of consumer adoption for both production technologies and FCEVs.

As these technologies become more cost-effective, long-term profitability becomes less of a point of hesitation for investors. This will allow for state financial support to decline and buildout to increase. Similarly, this will benefit the use of hydrogen in other energy service applications. Because vast buildout of renewable hydrogen production technologies for transportation use will lower the capital cost per kilogram of hydrogen per day produced by each method, this will have a positive effect on the adoption of hydrogen storage. As renewable hydrogen production emerges into its own market, it will become the object of innovation across sectors.

3. **A variety of viable scenarios are available for renewable hydrogen production infrastructure buildout, giving room for the market to determine next steps.**

Because ample feedstock and decreasing implementation costs for each technology are available, the future of renewable hydrogen production will be subject to market-driven preferences. In other words, the technologies that will become most widely adopted will be determined by industry stakeholders. To address this uncertainty in choice, various buildout scenarios were developed within this thesis that place emphasis on each technology and each demand scenario. The low-, mid-, and high-demand scenarios presented in this thesis account for the variability in transportation end-use amounts, and the high-electrolyzer, high-thermochemical, and high-anaerobic digestion cases account for the variability in technology adoption. It is unclear which technologies will become the preference of companies and their stakeholders; however, this work presents various feasible options, including two primary methods of hydrogen delivery. This is significant, given the desire to avoid driving markets and rather encourage market-driven preference. Providing suggested buildout scenarios to aid market-driven buildout will allow for investors to have the freedom to make their own business decisions and as a result of their autonomy, better prioritize the needs of the individual end-user.

4. **Future analysis in this area has a high potential to further guide and shape the implementation of each technology as it matures.**

To add to the depth of renewable hydrogen production infrastructure planning, a number of areas could benefit from greater study. First, a robust examination of the supply chain, to determine weak or failure points, would provide greater context to the delivery cost assumptions. This would entail a deeper look at production operations, transportation limitations, and inefficiencies associated with dispensing to the end user. It would greatly benefit the analysis and implementation of the technologies to understand their practical limitations and the scope of production facility operation requirements. This would improve the ability to identify priority areas in need of improvement or greater buildout to support the projected renewable hydrogen demand. Secondly, a more comprehensive feedstock analysis and land use analysis, done at the city and county levels, would provide a greater resolution for selected candidate development locations presented in this thesis. As stated in conclusion 1, a more robust feedstock analysis will increase the resolution of candidate development site locations. This will increase the ability to screen candidate sites for practicality. Similarly, a direct input of the station locations given by STREET can assist in increasing the spatial resolution of this work. This would involve the integration of the determined hydrogen refueling station locations and networks from STREET into the spatial demand inputs used within the Roadmap. Using a more comprehensive feedstock analysis as well as high-resolution demand points would allow for more specific locations for renewable hydrogen production technologies to be sited.

Lastly, continued tracking of the production technologies will be valuable feedback to the siting analysis, so as to determine which are being adopted in great numbers. As stated in conclusion 3, a variety of buildout scenarios are viable when considering the need to meet future renewable hydrogen demand. With decreasing costs, the scenarios that are adopted will be chosen by investors. Establishing and maintaining a database of all current projects, feedstock in use, and demand centers served will allow for informed planning of future projects. This will also allow for greater focus in future iterations of this work that will provide more detailed recommendations and buildout strategies.

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